



SYSTEMS ENGINEERING
Research Center

Introducing Model-Based Systems Engineering
Transforming System Engineering through Model-Based Systems
Engineering

A013 – Final Technical Report SERC-2014-TR-044

March 31, 2014

Principal Investigators

Dr. Mark Blackburn, Stevens Institute of Technology

Research Team

Dr. Rob Cloutier, Stevens Institute of Technology

Dr. Gary Witus, Wayne State University

Eirik Hole, Stevens Institute of Technology

Sponsor

NAVAIR, DASD (SE)

Task Order 033, RT 48

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 31 MAR 2014		2. REPORT TYPE		3. DATES COVERED 00-00-2014 to 00-00-2014	
4. TITLE AND SUBTITLE Introducing Model-Based System Engineering Transforming System Engineering through Model-Based Systems Engineering				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Stevens Institute of Technology, Systems Engineering Research Center, Castle Point, Hoboken, NH, 07030				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 59	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Copyright © 2014 Stevens Institute of Technology, Systems Engineering Research Center

This material is based upon work supported, in whole or in part, by the U.S. Department of Defense through the Systems Engineering Research Center (SERC) under Contract H98230-08-D-0171 (Task Order 033, RT 48). SERC is a federally funded University Affiliated Research Center managed by Stevens Institute of Technology

Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the United States Department of Defense.

NO WARRANTY

THIS STEVENS INSTITUTE OF TECHNOLOGY AND SYSTEMS ENGINEERING RESEARCH CENTER MATERIAL IS FURNISHED ON AN "AS-IS" BASIS. STEVENS INSTITUTE OF TECHNOLOGY MAKES NO WARRANTIES OF ANY KIND, EITHER EXPRESSED OR IMPLIED, AS TO ANY MATTER INCLUDING, BUT NOT LIMITED TO, WARRANTY OF FITNESS FOR PURPOSE OR MERCHANTABILITY, EXCLUSIVITY, OR RESULTS OBTAINED FROM USE OF THE MATERIAL. STEVENS INSTITUTE OF TECHNOLOGY DOES NOT MAKE ANY WARRANTY OF ANY KIND WITH RESPECT TO FREEDOM FROM PATENT, TRADEMARK, OR COPYRIGHT INFRINGEMENT.

This material has been approved for public release and unlimited distribution.

Table of Contents

Acknowledgments	6
Executive Summary.....	7
1 Introduction.....	8
1.1 Objective	8
1.2 Accomplishments in Phase 1	9
1.3 Organization of Document	10
2 Task 1 - Assessing the State-of-the-Art MBSE	11
2.1 Task 1 - Process.....	11
2.2 Scenario Collection	12
2.2.1 Organizational Type	13
2.2.2 Organizational Scope	13
2.2.3 Factors Definition Example	14
2.3 Organizations.....	15
2.4 Discussion Summaries.....	15
2.5 Predictive Model.....	16
2.5.1 Rationale for Bayesian Networks.....	17
2.5.2 Data - Likert Scales (Ranked Scales).....	18
3 Task 2 - Common Model Lexicon	19
3.1 Ontology vs. Lexicon	19
3.2 Tool for Representing Word Relationships	19
3.3 The Lexicon	20
3.4 Sources of Information.....	21
3.5 Web Presentation	21
3.6 Recommendations Moving Forward.....	25
4 Task 3 - Modeling the Vision and Relating to the “As Is”	26
4.1 Context for Relating “As Is” Artifacts and Process to Vision.....	27
4.2 Modeling and Tools for the Vision.....	28
4.3 Straw man	29
4.4 Acquisition Guidance Model (AGM) Model	31
4.5 “As Is” Artifact Analysis.....	32
4.5.1 Model Transformation Rather Than Model Evolution.....	35
4.5.2 Digital and Physical Surrogates.....	37
4.5.3 Vision Model Reference Architecture.....	39
4.6 Scope to Program of Record through Digital Critical Design Review	40
4.6.1 Context for Program of Record System	40
4.6.2 Case Studies and Existence Cases	41
5 Task 4 – Integrated Framework for Risk Identification and Management	43
5.1 Predictive Models for Risk.....	43
5.2 Risk Framework Approach to Uncertainty Quantification Modeling and Prediction.....	44
5.3 Scope of the Risk Framework	45
5.4 Risk Framework Captures Knowledge	46
5.5 Risk Related Research	47
5.6 Risk of SE Transformation to MBSE	47

6 Conclusion and Next Steps	48
Factor Definitions	50
Acronyms and Abbreviation	53
Trademarks.....	56
References	57

Figures

Figure 1. Four Tasks to Assess Technical Feasibility of “Doing Everything with Models”	7
Figure 2. Collection Instrument Results	12
Figure 3. Spreadsheet Instrument Collection	13
Figure 4. Bayesian Network Underlying Collection Instrument.....	17
Figure 5. Sample Graphic Representation from Ontological Software	20
Figure 6. Published Web Page from Data Collection Spreadsheet	23
Figure 7. Model Representation and Lexicon Tree	23
Figure 8. Partial Graphical Representation of Lexicon.....	24
Figure 9. Tabular Representation of Lexicon	25
Figure 10. Model Vision at Program of Record Scope and Integrate Risk-based Decision Framework.....	28
Figure 11. SysML Context of IWC Vision	29
Figure 12. I & I Environment	30
Figure 13. Vision Model Interface to Simulation and Test Resources	31
Figure 14. AGM Representations.....	32
Figure 15. System Engineering Technical Review Process Handbook	33
Figure 16. Derived Process.....	34
Figure 17. "As Is" Artifacts and Process Relationships.....	35
Figure 18. Notional Multi-level Crossing the V	37
Figure 19. System Level Maturity Representation for Development and Verification	38
Figure 20. Non-V Model System Level Maturity Representation for Development and Verification.....	39
Figure 21. Model Topology Often Mirrors Architecture of System	40
Figure 22. Mission Context for System Capability	41
Figure 23. Bayesian Model Derived from Airworthiness Factors.....	44

Tables

Table 1. Discussion Groups by Category 15

Table 2. Initial Lexicon Capture Tool..... 21

Table 3. "As Is" Artifacts..... 34

Table 4. Discussion Instrument Factor Definition 50

Acknowledgments

We wish to acknowledge the great support of the NAVAIR sponsors and stakeholders, including stakeholders from other industry partners that have been very helpful and open about the challenges and opportunities of this promising approach to transform systems engineering.

We want to specifically thank Dr. Dave Cohen who established the vision for this project, and our primary NAVAIR team, Jaime Guerrero, Larry Smith, Ernest (Turk) Tavares and Ron Carlson, who has worked closely on a weekly basis in helping to collaboratively research this effort.

We also want to thank all of those stakeholders, including some from industry that will remain anonymous in recognition of our need to comply with proprietary and confidentiality agreements associated with Task 1.

As there are so many stakeholders that supported this effort, we wish to recognize them all. We seriously apologize if we have missed anyone else that has supported our efforts.

Andrew Devine	Doris Schultz	Leslie Taylor	Scott Lucero
Art Pyster	Fatma Dandashi	Michael Gaydar	Shahram Bavani
Aumber Bhatti	Jae Pfeffer	Mike Kelley	Stan Rifkin
Bill Brickner	James Carroll	Paul Montgomery	Stu Young
Brad Kidwell	John McKeown	Philomena Zimmerman	Todd Standard
Dale Moore	Judith Dahmann	Richard Yates	Tom Blakely
Dennis Reed			

Executive Summary

The Systems Engineering Research Center (SERC) research task (RT-48) focuses on a Vision held by NAVAIR's leadership to **assess the technical feasibility** of creating/leveraging a more holistic Model-Based Systems Engineering (MBSE) approach. The expected capability of such an approach would enable mission-based analysis and engineering that reduces the typical time by at least 25 percent from what is achieved today for large-scale air vehicle systems. The research need includes the evaluation of emerging system design through computer (i.e., digital) models. The first phase of the effort began investigating the technical feasibility of moving to a "complete" model-driven lifecycle and includes four tasks as shown in Figure 1. The key tasks include:

- Task 1: Surveying Industry, Government and Academia to understand the state-of-the-art of a holistic approach to MBSE
- Task 2: Develop a common lexicon for MBSE, including model types, levels, uses, representation, visualizations, etc.
- Task 3: Model the "Vision," but also relate it to the "As Is" process
- Task 4: Integrate a Risk Management framework with the Vision

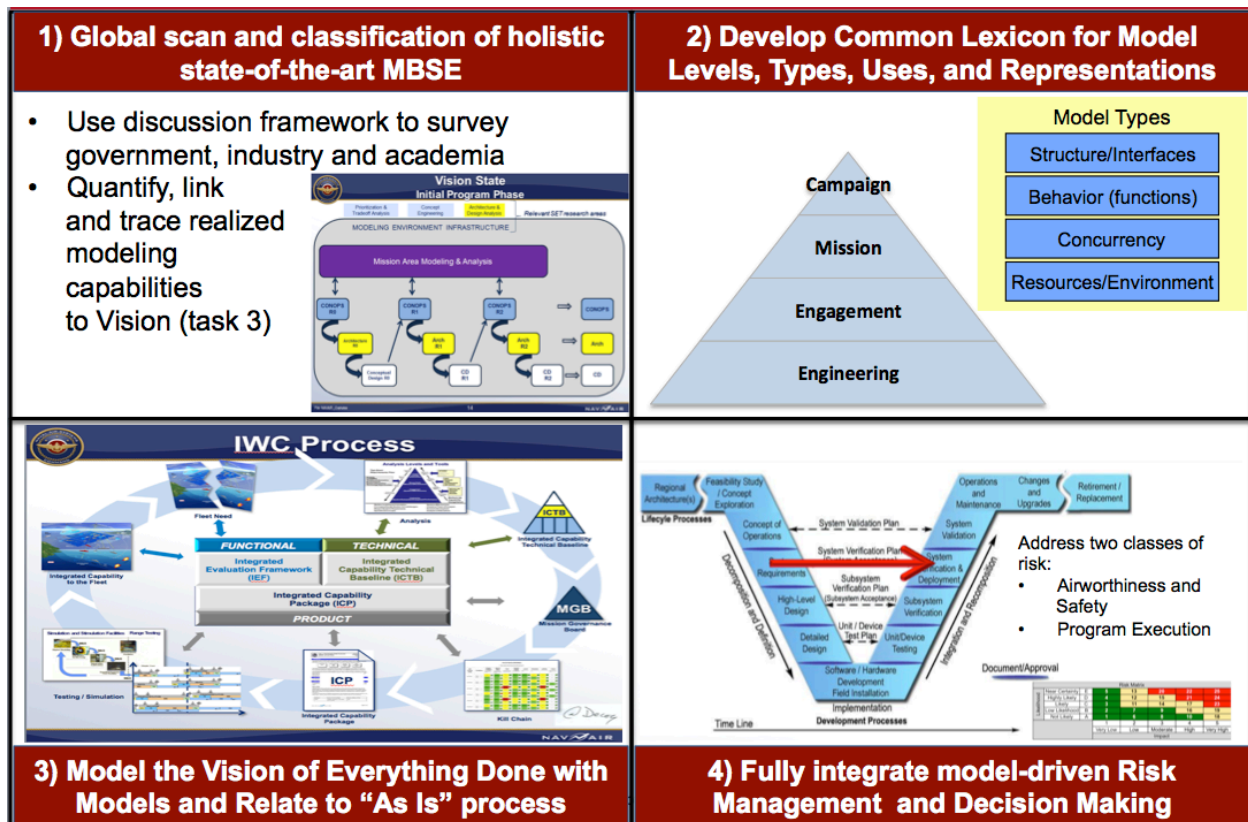


Figure 1. Four Tasks to Assess Technical Feasibility of "Doing Everything with Models"

The NAVAIR sponsor envisioned this research effort would take approximately two years, but due to the ending of the original SERC contract in December of 2013, this first phase (Phase I) had a period of performance of nine months. This report provides details about each task, the focus of the research questions, accomplishments, and the plans for the Phase II efforts, which are to continue under RT-118.

1 INTRODUCTION

In 2013, Naval Air Systems Command (NAVAIR) at the Naval Air Station, Patuxent River, Maryland initiated a research task (RT-48) to assess the technical feasibility of creating/leveraging a more holistic Model-Based Systems Engineering (MBSE) approach to support Mission-based Analysis and Engineering in order to achieve a 25% reduction in development time from that of the traditional large-scale weapon systems. The research need included the evaluation of emerging system design through computer models. The first phase of the effort created a strategy and began collecting and structuring evidence to assess the technical feasibility of moving to a “complete” model-driven lifecycle.

The larger context of the NAVAIR mission seeks a Transformation of Systems Engineering (SE) through MBSE, where MBSE¹ is used in the most general way. A key goal is to leverage virtual designs that integrate with existing systems data and simulations, as well as surrogates at varying levels of refinement and fidelity to support a more continuous approach to systems, Family of Systems (FoS), and Systems of Systems (SoS) analysis of alternative (AoA) and design refinement. Tradeoffs in this context would consider potentially non-optimal solutions that can close the gaps most rapidly to support the warfighters efforts in averting new or emerging threats. This should allow for proposing solutions to the mission/capability gaps, given both cost and time constraints and tradeoffs, but be significantly faster than using the current process while satisfying critically important safety and airworthiness requirements.

The Vision of NAVAIR is to establish an environment to evaluate the emerging system design through computer models and demonstrate system compliance to user performance and design integrity requirements, while managing airworthiness risks. It is anticipated that the use of models can streamline or radically transform the decomposition of requirements and their subsequent integrated analysis, which is currently aligned with the Department of Defense (DoD) systems engineering V-model. By providing more tightly coupled and dynamic linkage between the two sides of the traditional “V,” more efficient and focused requirements decomposition would eliminate thousands of pages of documentation delivered via contract data requirements that now substitute for directly invoking, manipulating, and examining the design through computer-based models.

1.1 OBJECTIVE

The overarching and potentially controversially worded research question is:

- Is it technically feasible to “do everything with models?” (the Vision)

The emphasis by the sponsors is on the “technical feasibility” of such a Vision. It is acknowledged that there are many possible hurdles beyond technical feasibility (e.g., organizational adoption, training, usability, etc.), but they have in general been reduced in priority for this phase of the effort.

There are many additional research questions such as:

- What are the emerging technologies and capabilities that will enable this Vision?
- How will such a Vision work in the face of complex, human-in-the-loop, autonomous, and adapting system?
- Can such approaches work in the face of safety and airworthiness requirements?
- What are the technical gaps limiting the Vision?

¹ Some use the term Model Based Engineering (MBE), Model Driven Engineering (MDE), or Model-Based Systems Development (MBSD).

- What are the approaches to deal with risk when making decisions based on virtual models and the associated simulations, surrogates and analyses?

There are four key tasks, which are described in this report, but a key decision made during the kickoff meeting was to attempt to “model the Vision” the rationale being that:

If one can “do everything with models” then we should be able to “model the Vision.”

The plan is to look to Industry (both contract developers of NAVAIR systems and MBSE technology providers), Academia and Government to identify the most advanced holistic state-of-the-art approaches to MBSE and represent those aspects and characteristics in the “modeled Vision.” There are some things that will likely be challenging to model, at least for now (e.g., human cognitive system interactions), and therefore there will be a risk framework integrated with the Vision. This risk framework will also leverage other types of predictive models (e.g., stochastic) to both embed decision-making knowledge and formalize both quantitative and qualitative information to support risk-informed decision-making.

1.2 ACCOMPLISHMENTS IN PHASE 1

During Phase 1, the objectives for the research needs were refined through meetings and working sessions held at NAVAIR. The tasks initiated during for Phase 1 included:

- Task 1: Surveying Industry, Government and Academia to understand the state-of-the-art of a holistic approach to MBSE;
 - Created and refined a discussion collection instrument, associated measurement model, and usage guidelines through an initial set of discussions with industry, government, and academic organizations
 - The discussion instrument identifies those indicators of capabilities that are the most state-of-the-art, which align with NAVAIR’s Vision (e.g., “crossing the virtual V”) while assessing risks such as airworthiness and safety
 - The discussion instrument provides a way to transform subjective expert judgments into a probabilistic quantity to provide a means for assessing the technical feasibility of the Vision
- Task 2: Develop a common lexicon for MBSE, including model types, levels, uses, representation, etc.
 - Created a lexicon using a template-based collection and website generation mechanism, with visualization for continually capturing and refining the lexicon that defines terms related to models
- Task 3: Model the Vision and relate it to the “As Is” process; this is an ongoing process to:
 - Identify “As Is” artifacts, model their relationships and characterize the process in a model
 - Develop mappings from the “As Is” artifacts to model-based candidates for the Vision
 - Created a “straw man” to describe the concept of a model-based Vision
 - Scoped effort to Programs of Record
- Task 4: Integrate a Risk Management framework with the Vision;
 - Identified and documented the strategies being researched by other organizations and identified key challenges with the Vision concept of “model everything” (e.g., dealing with classes of problems not easy to model: human cognitive properties)

1.3 ORGANIZATION OF DOCUMENT

Section 1 provides a statement of the research objectives, overview of the current progress and organization of this report.

Section 2 describes the approach for having discussions with commercial, government, and academic organizations in order to assess the most holistic state-of-the-art use or vision for MBSE. This section provides also a description of a discussion measurement instrument and model that is being used to transform subjective information into a quantitative representation.

Section 3 describes the approach for developing a model lexicon to characterize such things as: model levels, model types, model uses, representations, and other categories related to “models.”

Section 4 discusses the scope and concept of the Vision model and its relationship to the “As Is” artifacts and process that are currently in place for developing NAVAIR air vehicle systems; this also includes the airworthiness process.

Section 5 discusses a framework for risk identification and management that is primarily focused on how airworthiness and safety risk can be integrated in the Vision model, but it will also deal with program execution risks.

Section 6 provides some conclusions with a brief summary of the planned next steps.

There is additional backup information, including a list of acronyms and abbreviations following the conclusion.

2 TASK 1 - ASSESSING THE STATE-OF-THE-ART MBSE

Commercial, government, and academic users of MBSE have seen a steady rise in multi-level and multi-domain model, analysis and simulation capabilities. The emerging environments support varying degrees of fidelity that connect to different and complementary views of the system under analysis and design. The rise of high-performance computing has increased modeling and simulation capabilities and made large-scale models accessible.

Our team developed and refined a guideline for our collective NAVAIR team to hold discussions with Industry, Government and Academia (organizations) to understand the most state-of-the-art and holistic approaches to MBSE. The objective for our team members is to facilitate conversations through discussions that draw out insights into leading advances in MBSE. We agreed early on with the sponsor that open-ended discussions, as opposed to surveys, would bring out new and more innovative MBSE-related approaches and strategies. We are particularly interested in demonstrations of actual technical capabilities, but want to understand the critical gaps and limitations too.

We created a collection instrument. The instrument provides a constructive approach to conduct a discussion with organizations as well as a way to provide some type of quantitative measure associated with using subjective information to rate the “state-of-the-art” of a holistic approach to MBSE. We are using a qualitative subjective approach that computes a probabilistic value associated with crosscutting aspects (factors) associated with the technical Vision for this task.

The collection instrument uses an Excel spreadsheet as the input mechanism to collect factor values about an organization’s use of MBSE as discussed in Section 2.2. Each row in the spreadsheet represents the subjective information associated with one organization. The latest version of the instrument includes one organizational classifier and 22 factors. We have tested the instrument with eight different organizations covering different domains and perspectives. We have refined the instrument based on feedback from our team’s use, and will continue to do so, as necessary, as we have meetings with other organizations.

The following provides additional details related to the Task 1 effort, process, and approach.

2.1 TASK 1 - PROCESS

After a meeting with an organization, we request two things from our team members who conducted the discussion:

- Complete one row of the spreadsheet; see Section 2.2 for details on the collection process
- Write a short summary reflecting on the key unique capabilities of the organization

The spreadsheet responses will be incorporated in a master list. The value for each factor will be entered in a modeling tool, which quantifies the subjective inputs provided to the tool, as shown Figure 2. The maximum value of the mean of the probability distribution is 100. As reflected in Figure 2, it was decided that because there are some organizations that require confidentiality or proprietary information agreements, we have decided to keep the names of all organizations anonymous. In addition, a narrative will be created for each organization; this narrative will highlight the most key capabilities and challenges, but be generalized to ensure each organization’s anonymity. Additional details about interpreting the results are provided in Section 2.2.

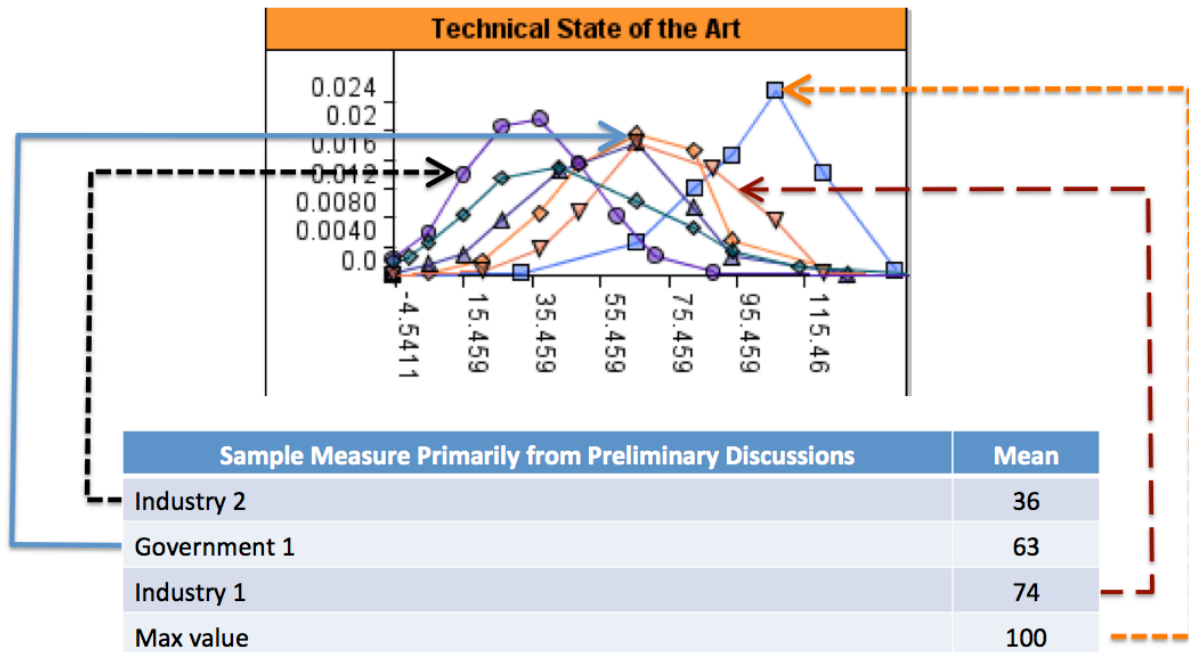


Figure 2. Collection Instrument Results

2.2 SCENARIO COLLECTION

Our team members engage in the discussions with organizations, and complete the spreadsheet collection mechanism as shown in Figure 1 at the conclusion of the meeting. He/she works through the row and uses the pull down menus to select a factor value of Low, Medium, or High (see Section 2.5.2 for details on Ranked factor values). A complete list of factors is provided in a worksheet tab of the spreadsheet collection mechanism titled: Factor Meaning-Definition. Example definitions are provided in Section 2.2.3, with some additional rationale; a complete set of definitions is provided in Discussion Collection Instrument Guide and provided in the back up material of this report.

Team members may want to use one spreadsheet to collect all of the discussions; it is possible and acceptable that after a few meetings with organizations that one or more of the factor values be changed in order to be more globally consistent. The key is not to identify a particular organization, rather the objective is to identify if there are state-of-the-art methods, tools, processes and innovative strategies that are being used to significantly advance the development and deployment of systems through MBSE and related approaches, and to incorporate these concepts in the Vision model (see Section 4).

Organization Name				Organizational Scope										Factors (by Category)											
Organization (consider the use of an anonymous ID)	Candidate Factors																								
	Magnitude	Proven	Crossing Virtual V	Cross Domain Coverage		Virtual System Representation		Management Criticality Risks (Relates to Task 4)		Attributes of Modeling Maturity		Operational Risks (Relates to Task 4)		Indirect support from Models											
Industry, Academia, Commercial, Government, Other	Organizational Scope	Scope Impact	Demonstrations	Integrated Simulation	Formal Analysis	Domain Specific	Domain Interoperability	Synthesis/Generation	Meta-Model/Model Transformations	Surrogate Integration	Formal Capability Assessment	Virtual Accuracy/Margin Analysis	3D Immersive Environments	Risk Management	Predictive Analytics	Model-based metrics	Multi-model interdependencies / consistency and semantic	High Performance Computing (HPC)	Procedures	Staff and Training	Human Factors	Certification	Regulation	Modeling and Simulation Qualification	
Industry 1	Site	Med	Pick	Low	Low	High	Pick	High	Med	Low	Low	Low	High	High	High	Low	Low	Low	Low	Low	Low	Med	High	High	
Academia 1	Department	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	
Commercial 1	Business Unit	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	
Government 1	Program	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick	

Menu for selecting factors value (L, M, H)

Figure 3. Spreadsheet Instrument Collection

2.2.1 ORGANIZATIONAL TYPE

The general convention used is:

- Academia – this should include strictly academic organizations; other organizations performing research should either be Industry, Commercial or Government
- Industry – these are organizations that are using MBSE to develop products and systems (e.g., those contractors to NAVAIR that produce air vehicle systems)
- Commercial – this is a special case of Industry that relates to MBSE product developers
 - These organizations either develop MBSE tools and services, or may apply them with Industry or Government customers
 - These organizations are in the list, because they may have insights into some of the leading or novel uses of the tools, and they are aware of the need to continually advance their own product and services
- Government – this includes military, and other non-military organizations such as Department of Transportation, and the FAA

2.2.2 ORGANIZATIONAL SCOPE

One challenge for some of the initial uses of the collection mechanism was to appropriately reflect on the organization scope for which these MBSE usage questions apply. Remembering that the key objective of the survey is to assess the "Technical Feasibility" of "doing everything with model." We recognize that actual adoption can be difficult, and might not make sense on older systems. Therefore it is probably best to hold discussions with individuals in the roles such Chief Engineer, Chief Technical Offer, Program Manager or some MBSE technical experts in the organization. To carry this a step further, it might also be important to keep the "systems" perspective in mind, because some of the concepts discussed may have been applied at the hardware level and possibly in types of software (e.g.,

the control laws for the F35 are built in Simulink, with auto code generation, and a significant portion of auto test generation), but these types of approaches may only be emerging in use at the systems level. We seek to understand how comprehensive the use, and also **need to understand the technical gaps**. The technical gaps areas will likely need to have additional focus related to risk management (Task 4).

Finally, this research is not limited to NAVAIR, however when thinking about NAVAIR systems the scope is often quite large and involves large-scale multi-year programs, where the systems are actually built by one or more contractors.

Therefore, we would like to know the organizational scope associated with the MBSE discussion: Program, Project, an entire Business Unit, Platform (e.g., a type of a specific aircraft, tank, automobile), Department, or Site.

2.2.3 FACTORS DEFINITION EXAMPLE

The factor categories do not necessarily relate to specific MBSE practices, rather they are higher-level characteristics of the organization's ability to leverage the use of models and the associated technologies that enable simulations and accelerate the analyses, design, synthesis, V&V and manufacturing processes. For example:

- **Crossing the Virtual V** is a high-level category that has significant weighting in the model, because our sponsor emphasized this as a critical need and the ability to understand the design capabilities through early V&V activities at the system and mission level (as opposed to the subsystem or component level). Therefore, this factor category has three main factor characteristics:
 - Simulation of Integration
 - If an organization has simulations of integration or integrated simulations across domains of the system, and especially at the "higher" levels of the "V," this is a likely indicator that such an organization is likely to have the ability to understand simulations of the system within the context of a mission, and there is a better understanding of the integration impacts, because the simulations are integrated or represent integration, including critical temporal aspects in simulation
 - This includes the integration of surrogates, use of instrumented systems, actual system components, new prototypes, and/or in development
 - Other attributes of this type of simulation, would be human-in-the-loop, as well as multi-level mixed fidelity simulations that provide the right abstractions at the right level
 - Formal analysis
 - This means that the analysis is automated, because the models are semantically rich; we are looking for automated analysis, rather than looking at humans performing the analysis
 - Models are increasingly have more semantic richness that enable automated-types of analysis, and models are increasingly being integrated (see factor category **Cross Domain Coverage**)
 - Domain specific
 - These types of systems involve the integration of many disciplines
 - Models need to provide the relevant abstractions that are related to the domain of the engineer performing the work; domain-specific modeling is an emerging type of modeling that often provides the relevant abstractions, with the semantic richness to enable automated analysis, simulation, synthesis (generation) and automated test

- DARPA-sponsored research that demonstrated the capability for continuously evolving Domain Specific Modeling and analyses in 2008 as an emerging capability and theme [16], [33]. In contrast, modeling languages like System Modeling Language (SysML) are general purpose [24] they generally lack the semantic richness needed for formal analysis leveraging for example formal methods of automated V&V [9]; while they may be understood by system engineers, control system engineers would prefer Matlab/Simulink, and other engineers may require other domain-specific models and tools (e.g., computational fluid dynamics, radio-frequency, heat transfer). However, SysML does provide an underlying framework for holding system model information [36], yet the models are not executable even with existing plug-in authoring tools [13] (see Section 4.2 for more details).

2.3 ORGANIZATIONS

Table 1 shows the current distributions of the planned discussions.

Table 1. Discussion Groups by Category

Discussion Groups		
Category (needs discussion)	Preliminary Held	Planned/In Process
Commercial – provides tools and/or service to produce systems	3	2
Industry - produce systems	2	8
Government	2	6
Academia/Consortium Hybrid		2

2.4 DISCUSSION SUMMARIES

We request small narratives for each organization, where the discussion should highlight those organizational uses of MBSE that represent the greatest advances.

For example:

An industry organization provided a historical perspective on evolutionary adoption of MBSE. Some of the more exceptional characterization related to advances they have made that included: composable designs, common platforms, catalogs of capabilities, and synthetic representations of the environments. Much of their efforts were grown out of SysML-centric approaches. They are actively using model-based metrics, Live-info for simulation, predictive analytics based SysML, interpreting and tracing data consistency across disciplines, data set metric, trusted models for downstream production, PDM consistency and semantic links; these efforts include working the MBSE efforts top-down and bottom-up, starting first with an understanding workflow, and meta-spec concept.

As a second example, we talked with a SME from the Department of Transformation that has been involved in crash testing of automobiles for many years. The focus of our question was not as broad as the factors covering the lifecycle of a NAVAIR program, but more interested in the question: ***“are***

automotive companies reducing the number of crash tests through the use of model?” While, we did calculate a score for the responses, some of the factors may not directly relate, and therefore, we are requesting a narrative to help with elevating awareness of specific uses of models that may have relevance to the overall research task. There is a factor in the model that describes **Scope Impact**, this value is used to characterize the scope of an organization’s use of models.

2.5 PREDICTIVE MODEL

This section is provided for those interested in more details about the mechanism for converting the subjective factors into a quantitative number. The model is created using a Bayesian Network [32] (BN) tool. There are two basic reasons we selected this approach, BNs:

- Provide for the translation of subjective information into quantitative probabilities
- Allows for the use of subjective expert qualitative judgment and captures the casual relationship between subjective factors

The outputs are also probability distributions, which means that they provide some type of range to provide a comparison between different organizations. The specific numbers are not necessarily as important as our ability to compare different organizations and relate the responses back to advanced uses of MBSE and related enabling technologies. While no organization may have all “High” values, this approach provides a way to look at relative comparison in conjunction with the narratives. Each of the nodes in the BN shown in Figure 4 provides a type of weight called a conditional probability. We have used the team’s judgment to weight the different nodes in a way that would relate to evaluating the key question for this task: is it technically feasible to “do everything with model.” In addition, we will refine the weightings as we proceed through discussions.

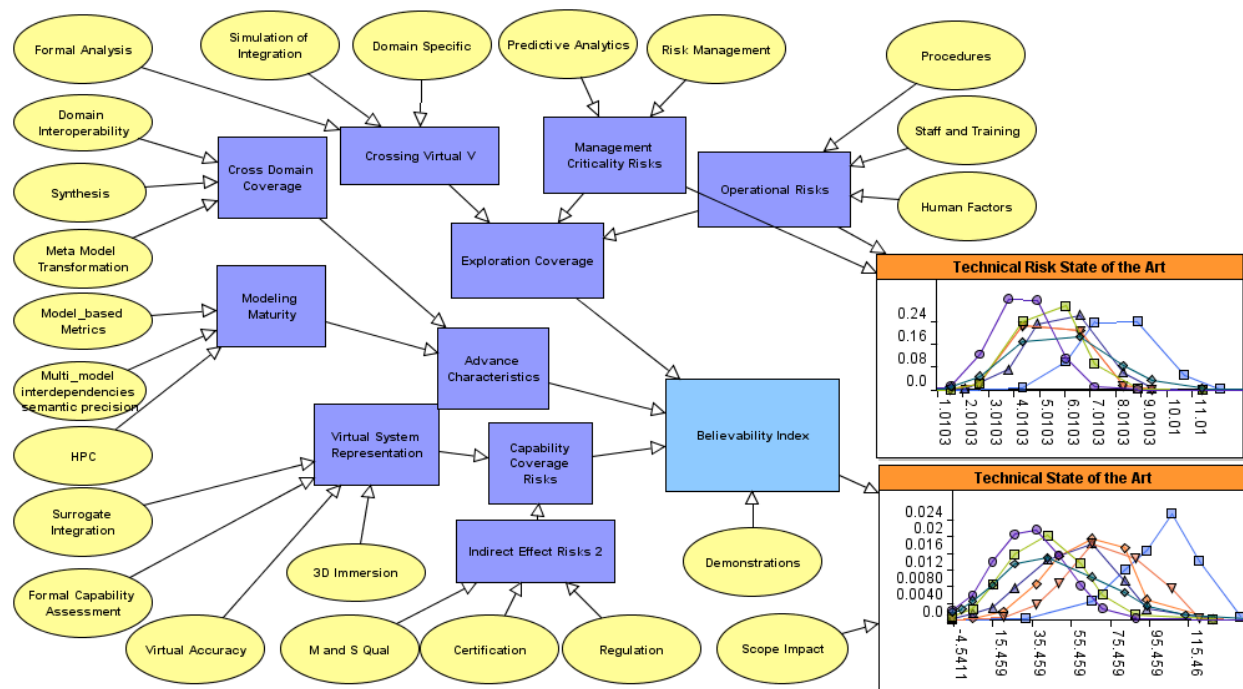


Figure 4. Bayesian Network Underlying Collection Instrument

2.5.1 RATIONALE FOR BAYESIAN NETWORKS

A Bayesian network is a representation, which organizes one's knowledge about a particular situation into a coherent whole [17]. They are increasingly being used in the modeling of uncertain and incomplete knowledge. Bayesian thinking is inherently more intuitive than many other evaluation techniques; it best reflects commonsense thinking about uncertainty that humans have. We frequently use words like "likely," "rarely," and "always" to express varying degrees of uncertainty. Subjective probability is our way of assigning numbers (between 0 and 1) to these different degrees of uncertainty, and our probabilities can change as we are presented with new information, or we have new experiences which cause a shift in beliefs or expectations. When this shift occurs, the way our probabilities change are governed by Bayes' rule.

A Bayesian network, as used in this framework, is a joint probability distribution and as such, any question that can be asked in a probabilistic form can be answered with a stated level of confidence. Some typical questions might be:

- Given a set of effects, what are the causes?
- How can an outcome be controlled, given a set of circumstantial values?
- If we model a causal relationship, what result would an intervention or change bring?

While there are several ways to structure a Bayesian network, we used prior experience to structure the model. The subjective factors in the spreadsheet instrument map directly to the yellow oval nodes of the BN model. The purple rectangles are intermediate nodes and generally relate to factor categories. The orange rectangles represent the probability outputs of both Technical state of the art (Task 3) and the Technical Risk state of the art (Task 4).

2.5.2 DATA - LIKERT SCALES (RANKED SCALES)

The subjective factors in the model use a Ranked node type, which is a type of Likert Scale. It is important to note that although Likert scales are arbitrary, they can retain a level of reliability for our use. The value assigned to a Likert item has no objective numerical basis, either in terms of measure theory or scale (from which a distance metric can be determined). In this case, the value assigned to a Likert item has been determined by the researcher constructing the Bayesian network, but can be refined as the research progresses. The results have been a balanced representation of strata and detail.

Typically, Likert items tend to be assigned progressive positive integer values. Likert scales usually range from 2 to 10 – with 5 or 7 being the most common. In this model, 3 levels are used, at least for now as it minimizes the number of computational states, which minimizes time for the analysis. The progressive structure of a Likert scale is such that each successive Likert item is treated as indicating a ‘better’ response than the preceding value. Note that the direction of ‘better’ (i.e., Higher) depends on the wording of the factor definition, which is provided in Section 2.2.3.

In terms of good practice, a bias in the computations may result if the suppliers of data for the framework do not agree on the relative values of each factor. However, there are enough factors that a bias in a one or two values will likely not skew the results significantly.

3 TASK 2 - COMMON MODEL LEXICON

The team realized early the need for a common lexicon when discussing modeling in the systems engineering domain, and in fact, in the broader engineering space. An example of this is what is meant by the word "model." Most engineers will agree that a model is a facsimile of reality. Yet, to an industrial engineer, a model may represent a production facility; to a mechanical engineer it may be a finite element model analysis; to a systems engineer it may be an IDEF0 or a SysML representation of the system, subsystem, or some lower level element. None of those perspectives are wrong; they are just different views of some part of the same enterprise.

Therefore, a task was established to define terms used across the engineering modeling landscape. Some claim that there is no existing model lexicon or taxonomy [2], although there are a number of different types of taxonomies that all fit within the more general context of a model lexicon [14], [36]. The Object Management Group (OMG) in conjunction with INCOSE has established an Ontology Action Team to work on similar efforts [30]. The NDIA Modeling & Simulation Committee is about to approve the Final Report on the Identification of Modeling and Simulation Capabilities by Acquisition Life Cycle Phase [3]. For NAVAIR, this was an immediate need for our research task and we were tasked with developing a common lexicon.

3.1 ONTOLOGY VS. LEXICON

According to Wikipedia, ontologies are the structural frameworks for organizing information and are used in artificial intelligence, the Semantic Web, systems engineering, software engineering, biomedical informatics, library science, enterprise bookmarking, and information architecture as a form of knowledge representation about the world or some part of it [35]. The creation of domain ontologies is also fundamental to the definition and use of an enterprise architecture framework.

A lexicon is a similar concept – it is normally a book or glossary like document, or words (and their definitions) in a language or domain, arranged in alphabetical order. The team decided that a simple glossary would not be sufficient because it does not show the relationships between terms.

In simplistic terms, an ontology becomes a complex network of words, and their relationships to each other. A lexicon is a glossary. Neither was exactly what was needed for this project. Instead a hybrid is needed. The team needs something that provides definitions and simple relationships – not complex, rigid definitions. We chose to use the word Lexicon, though the words could also be represented in a tree-like structure that is common for ontologies.

3.2 TOOL FOR REPRESENTING WORD RELATIONSHIPS

There are tools available for creating ontologies. There actually exists a class of workers that consider themselves Ontologists. These tools come in many different flavors – from open source tools to commercial tools. The common thread is that they create graphical representations as shown in an example in Figure 5. These tools require rather rigorous definitions and relationships to complete. The open source tools are actually very good, and very robust. However, after some evaluation of available open source tools, the team decided that it would be better to create a straightforward spreadsheet of terms (e.g. a Lexicon), and then create a script that could represent that lexicon graphically.

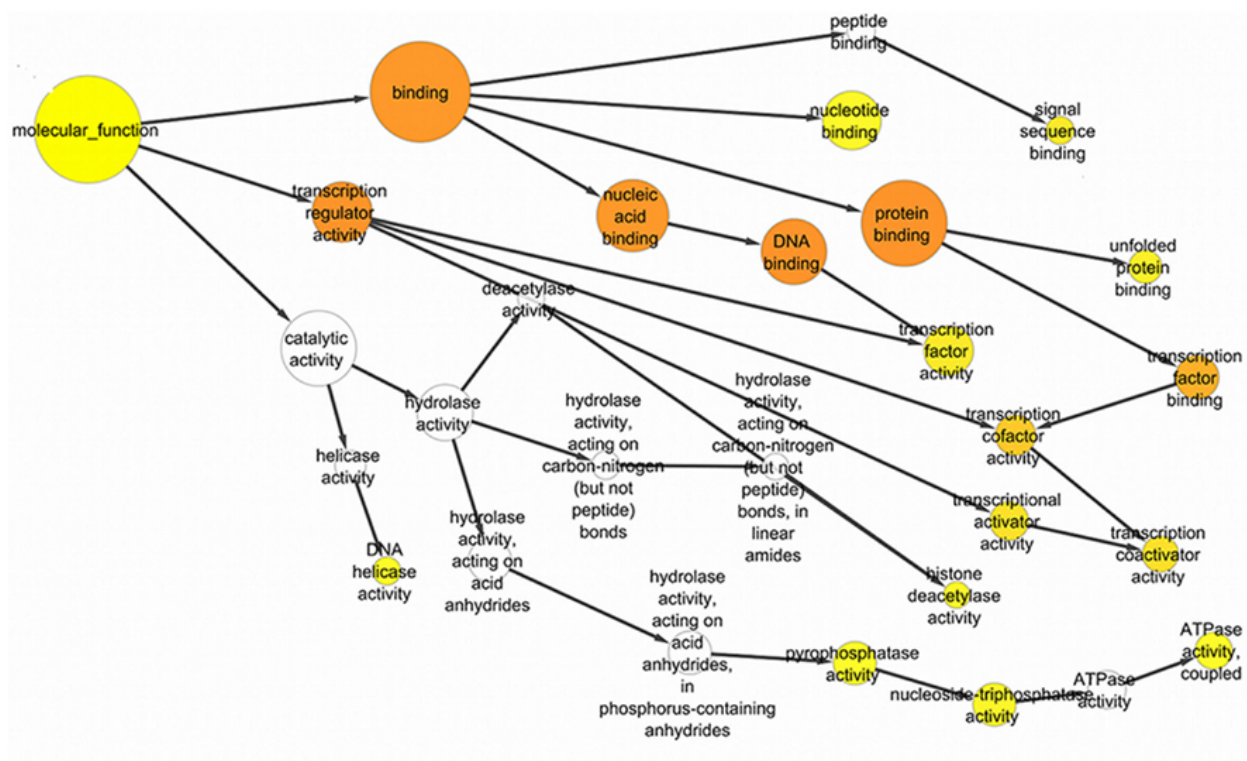


Figure 5. Sample Graphic Representation from Ontological Software

3.3 THE LEXICON

A spreadsheet was first created in Excel. At first, the team was simply capturing the words, their definition, and where it made sense, a key reference or two for that definition. Table 2 shows the implementation of this data gathering spreadsheet. Once the decision was made to create a tool to make this information available graphically, and also on the web, it became apparent that a "relationship" data element was necessary. Therefore, the data collection tool captures:

- Name
- Has Parents [0 or more] separate with ";" if more than one
- Definition
- Sample Usage
- Also Known As
- Key URL (optional)

The current spreadsheet represents a continuous accumulation of relevant terms, their definitions, and their classification. The initial definitions have been drawn from readily available sources on the Internet (often from Wikipedia where the assumption is that it has been created by a group of people with both knowledge and passion about the subject). In other cases members of the research team have authored a definition based on their understanding of the term in a relevant context. The team is using the spreadsheet feature of GoogleDocs to foster a collaborative effort.

Table 2. Initial Lexicon Capture Tool

Term	Definition	References
MBSE	Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.	(INCOSE, Systems Engineering Vision 2020, Version 2.03, TP-2004-004-02, September 2007)
MBSD	An engineering approach that promotes the use of models to develop, integrate and monitor systems across disciplines, environments and scenarios.	
MBE	Model Based Engineering - Model-Based Engineering (MBE) as an approach to engineering that uses models as an integral part of the technical baseline that includes the requirements, analysis, design, implementation, and verification of a capability, system, and/or product throughout the acquisition life cycle.	(NDIA – Final Report of the MBE Subcommittee)
Concurrent Engineering	reducing time between project launch and delivery by operating elements of the process in parallel. Concurrent engineering is simply a practice of doing as much of the system life cycle design and development in parallel as possible with the inevitable rework associated with the risk of parallel development - as you get into more detail that will reveal findings that ripple back across the 'already' completed work since you are trying to tackle everything at once	

Intuitively, many of the terms in this spreadsheet are ambiguous and their meaning is highly dependent on the context and usage domain. This has been found to be true in reality also as terms are collected from various domains. It is therefore important to emphasize that this is an evolving process.

3.4 SOURCES OF INFORMATION

There were a number of sources used for this initial Lexicon. Journal papers on MBSE provided a good first cut. Interestingly, an article from the Journal of Object Technology [21] proved to be very useful. Other sources included The Open Group, the Object Management Group, INCOSE, NDIA, and Wikipedia.

3.5 WEB PRESENTATION

A short script was created that takes the information contained in the data-entry spreadsheet, and publish the results to the web. Figure 2 shows the published page as it looks at the time of this report, (http://www.markblackburn.com/MBSE/model_lexicon.html)². This page includes four sections:

- Model Lexicon Overview (Figure 6)
- Model Representation/Lexicon (Figure 8)
 - This is a generated image produced by vizGraph, but with over 300 lexicon items it is difficult to use, although it reflects the interrelationships of the lexicon elements
- Hyperlinked Tree of the Model Lexicon (Figure 7)
 - As an alternative, a collapsible and expandable tree (outline) allows people to understand the hierarchy of model lexicon with hyperlinks to a particular lexicon definition.
- Definitions - A common structure is used for each term (Figure 9)

² The final location of the lexicon may move to another location.

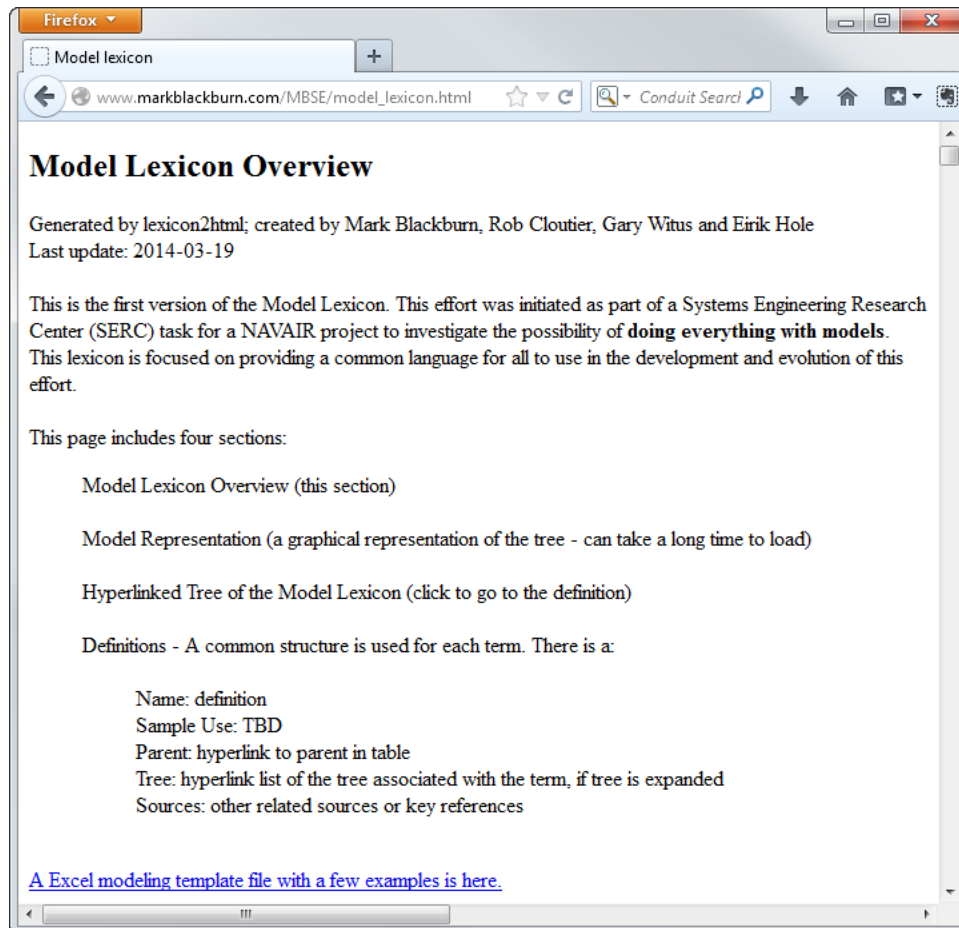


Figure 6. Published Web Page from Data Collection Spreadsheet

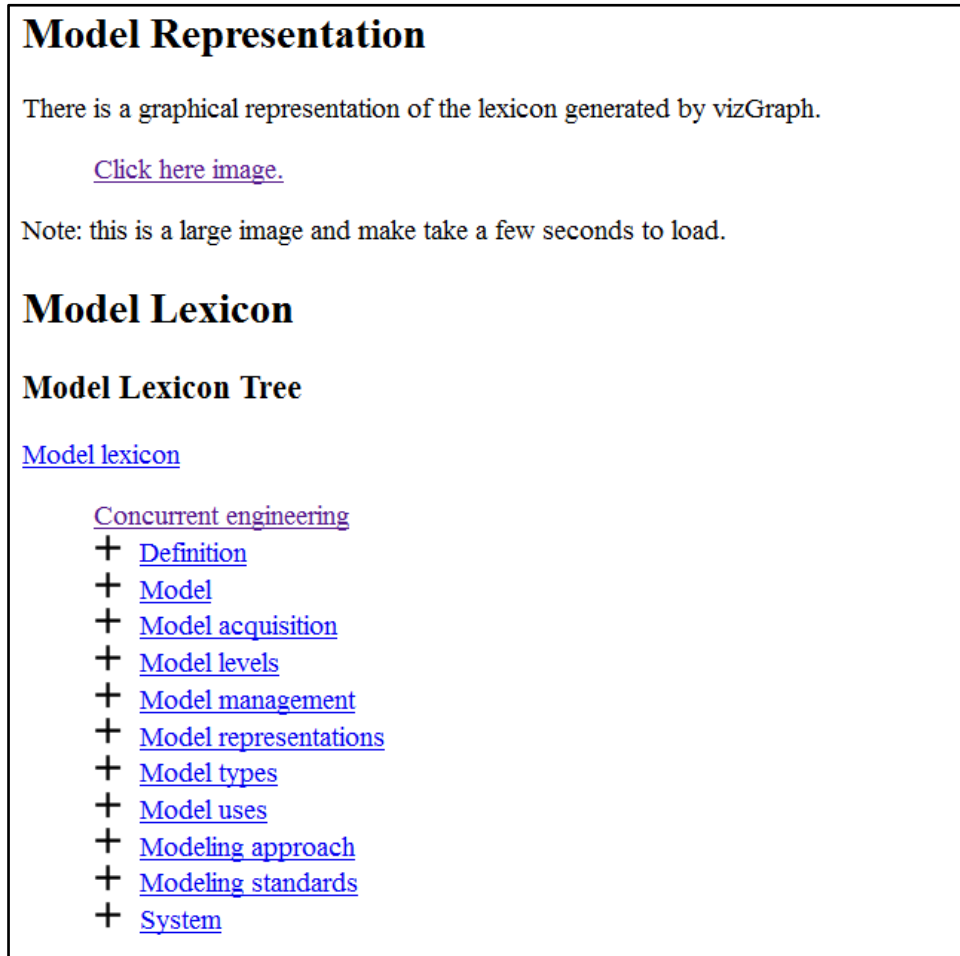


Figure 7. Model Representation and Lexicon Tree

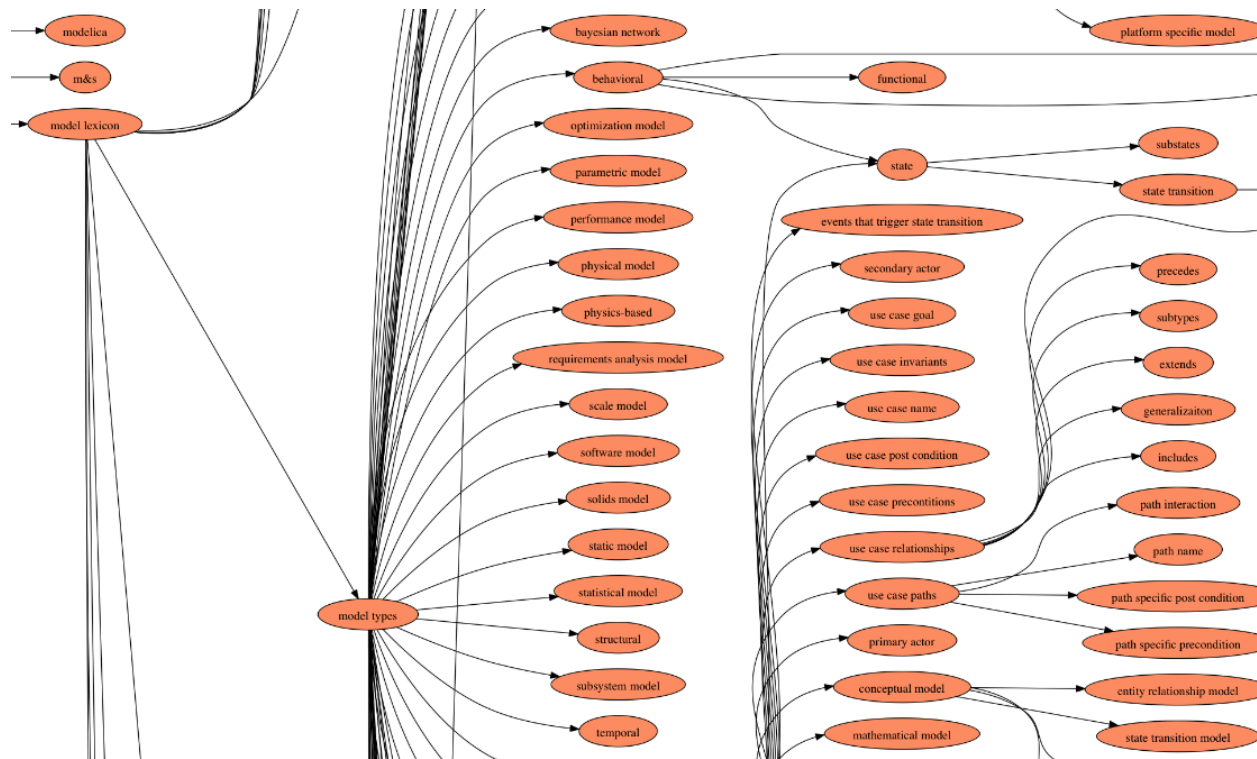


Figure 8. Partial Graphical Representation of Lexicon

The definitions table shown in Figure 9, is a screen image from the website, and includes the following columns:

- Name
- Definition
- Parent
 - This is a hyperlink to the parent in the table
- Tree
 - This is a hyperlink back to the collapsible and expandable tree (outline); clicking on this hyperlink takes the focus back to the name in the tree only if the item is expanded in the tree
- Sample Use
- Key Source (if applicable)

Model Lexicon Definitions

Name	Definition	Parent	Tree	Sample Use	Source
2d modeling:	a geometric model of an object as two-dimensional figure, usually on the Euclidean or Cartesian plane	mechanical modeling	mechanical modeling, 2d modeling		
3d solid model:	the product of 3D solid modeling	mechanical modeling	mechanical modeling, 3d solid model		
3d solid modeling:	is the process of developing a mathematical representation of any three-dimensional surface of object (either inanimate or living) via specialized software	mechanical modeling	mechanical modeling, 3d solid modeling		
More Sample					
Model driven architecture:	a software design approach for the development of software systems	model technique	model technique, model driven architecture		http://www.omg.org/mda
Model levels:	Level of the system or system of systems; Also discussed in terms of Resolution level. The amount of detail or degree of aggregation employed in the model or simulation	model lexicon	model lexicon, model levels	Often used in modeling and simulation world to discuss the different types of models	
Model lexicon:	the words used in a language or by a person or group of people		model lexicon	This is a lexicon associated with terms derived from models and modeling	
Model management:	Approaches to managing models	model lexicon	model lexicon, model management	Configuration control, PLM, CATIA	

Figure 9. Tabular Representation of Lexicon

3.6 RECOMMENDATIONS MOVING FORWARD

1. We expect as the effort continues, team members will continue to collaborate in the definition and classification, causing discussion related to their relevance and “correctness.”
2. Additionally, the intent is that the broader community will contribute examples and sample usages of the terms to improve the understanding and proper use in various contexts.
3. We will therefore provide mechanisms that allow for feedback/annotation from the community and a basic change control process.
4. It might be good to add a “comment” link on each table row on the website that could link directly to the corresponding row in the Google spreadsheet to enable the submission of a new terms and definitions directly into the spreadsheet (or database).
5. A longer-term plan would be to drive the graphical image, and textual listing from a database instead of a spreadsheet.

4 TASK 3 - MODELING THE VISION AND RELATING TO THE “As Is”

The concept of the Vision model is not a representation of a NAVAIR air vehicle system, rather the Vision model must include the required information (data) and embedded knowledge that is normally captured in documents, drawing, specifications, pseudo-formal models, and tests (some refer to it as the “total” system model [37]). This includes or subsumes every piece of information that relates to the artifacts captured in the “As Is” process, but should also include formalized information such as the inputs and outputs of modeling and simulations, analyses, surrogates, risk information, etc. and include specific versions of each tool, simulation, and analysis engine used to support the necessary evidence required to produce an airworthy system version. Ideally, this should include every piece of information to the Bill of Material (BOM), including models to manufacturing and models to training.

Preliminary discussions with organizations suggest that some individuals and organizations understand the Vision model concept. Some are attempting to develop variants on the concept that are more specific to product development. Some have cross-business/discipline projects established to refine strategies to roll out and support adoption by programs in these different business units. Other efforts are focused more at the software level (using the characterization Model Driven Engineering [MDE]) [23]. One study cited a multi-level, multi-domain instance case that started at the campaign level moving down through the mission, engagement, and engineering levels [1]. There are also organizations that claim to be applying MBSE, yet they have not seen the benefits; we understand that there are often adoption challenges [10], and that is why our sponsor has directed us to focus on the technical feasibility for this phase of the research.

While we are just beginning to have discussions with organizations, it is a fairly consistent message that many organizations have not defined a Vision model. Instead they are involved in an evolutionary process of model adoption, and many want to better understand the return on investment. We don’t know some of the specific details yet as several of the proprietary discussions are in the coordinating stages (see Task 1). Key to NAVAIR is that we also do not know how well these efforts address some critically important requirements for NAVAIR such as airworthiness and safety. In addition, some of these organizations are working on a subset of the problem (e.g., V&V) [24], while others are approaching this from the contractor point-of-view, which is significantly different from that of NAVAIR. NAVAIR is working in the early stages of DoD 5000.02 [19] lifecycle (i.e., Milestone A, B, C), and they ultimately produce requirements and design constraints that are provided to the contractors. There is a significant amount of research needed on this task. Our approach is to work this effort in conjunction with our state-of-the-art discussions (Task 1).

The objective for the Vision should address the questions:

- Can we create models to cover every type of artifact that is required to produce a system and comply with DoD and NAVAIR processes and requirements (e.g., Airworthiness)?
- Can we use model-based simulation, analysis, synthesis and generation to rapidly traverse the “Virtual Vee” and continuously, both horizontally and vertically, leverage evolving digital representations (e.g., models, surrogates) to assess the system design at various levels of fidelity in the context of continuously evolving mission scenarios?
- How does the risk framework fit into the model?
- What would a “Model-Driven” process be? With model-driven processes there are many types of automated workflows engines that automate the processes inherent in producing and relating model-based artifacts (see Section 4.5.1 for an example)

4.1 CONTEXT FOR RELATING “AS IS” ARTIFACTS AND PROCESS TO VISION

We initially developed (as a straw man, see Section 4.3) an example model in System Modeling Language (SysML) that represented the Integrated Warfighter Capability (IWC). The example provided a common understanding that the goal of the modeled Vision is going to formally characterize all of the “data,” relationships, automation throughout the entire lifecycle, including for example the relationship to data used by, and produced by modeling and simulation, analyses and other resources, as well as evidence captured within the models to support risk assessment and management (see Section 5).³

From a high-level perspective, as reflected in Figure 10, Task 3 is a collaborative effort being worked by our SERC team, SMEs from NAVAIR, Naval Post Graduate School (NPS), MITRE, and consultants who have extensive NAVAIR and aircraft system engineering experience. This section provides a summary of our Phase I efforts. The following enumerates subtasks for Task 3 (the list order is aligned with the elements in Figure 10):

1. Developing a CORE⁴ model representation of a derived list of artifacts that are currently produced to support NAVAIR System Engineering Technical Review (SETR) process (see Section 4.5 for details)
 - It is important to understand the artifacts that are produced to comply with the “As Is” process, along with the relationship and dependencies among these artifacts
 - In the Vision, the information described in these artifacts (some of which are models today) must be ultimately represented in models (digital form), or be derivable from models
2. Representation of the “As Is” process, which relates to the DoD 5000.02 and SETR process
 - The analysis of the “As Is” artifacts and process should provide a means to assess the completeness of the Vision, and help people understand how a process would work when transitioning from a document-centric operational model to a model-centric approach
 - As we are looking to leverage existing results, in our first working session it was suggested that we look at the Acquisition Guidance Model (AGM) developed by MITRE [15] (see Section 4.4 for details)
3. Development of a representation of the Airworthiness Process⁵
 - This effort will characterize those critical aspects that make the NAVAIR requirements more challenging than for other organizations
 - The types of required Airworthiness evidence (e.g., Flight clearance) must be identified and presented either in some model representation (4) and/or support risk-based decision making, which should be captured in conjunction with the Vision (5)
4. Model representation that subsumes all information that is currently represented in the “As Is” process, if deemed to be necessary, and all of the associated digitized automation that is required to transform the process
 - This will be significantly informed by the discussions (Task 1)
5. The integrated risk framework (see Section 5 for details)
6. The associated process for apply the Vision model; in many instances, when the information is formalized in model, a corresponding model-driven automated workflow is also automated, however, because of the aspects of risk and airworthiness, it is likely that there are some human-driven steps in the process

³ There are number of useful representations and documentation that are not currently released for public viewing.

⁴ We are not promoting any specific modeling tool.

⁵ This effort was started in our February working session and is being supported by our MITRE team partner.

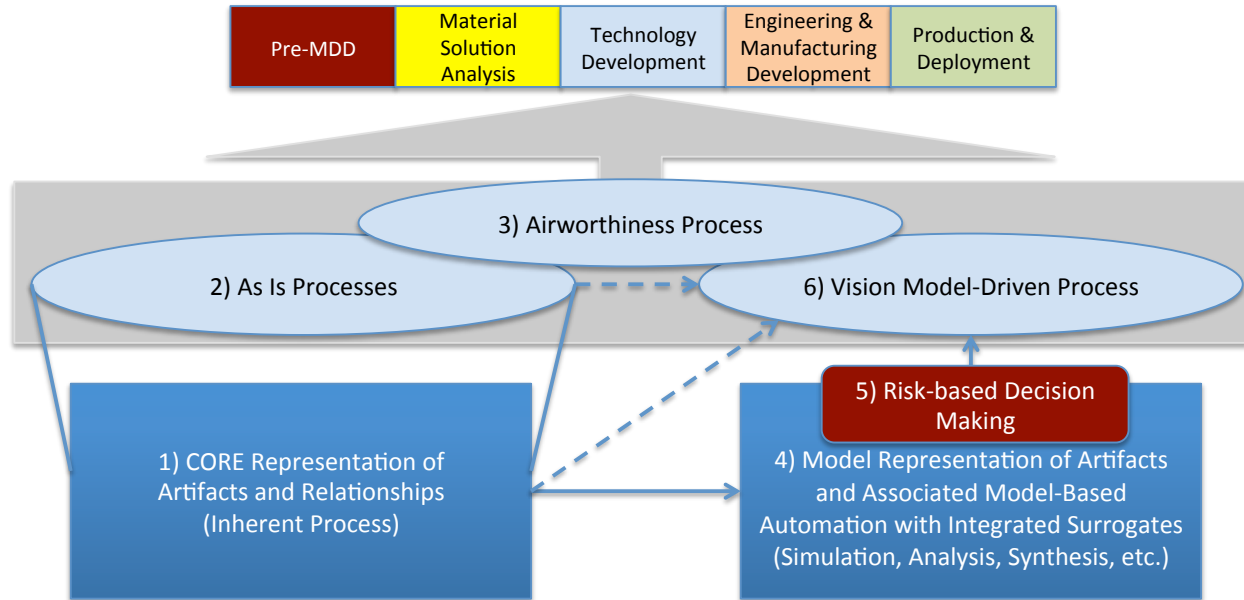


Figure 10. Model Vision at Program of Record Scope and Integrate Risk-based Decision Framework

The following subsections are presented primarily in chronological order associated with research investigation, working sessions, and task scoping and refinement.

4.2 MODELING AND TOOLS FOR THE VISION

Our team has had numerous discussions about modeling representations, languages and tools for the Vision. The examples in Section 4.3 use SysML, which is a standard modeling language. It is general [24], but there are limitations. The basic SysML diagrams in the modeling environments are mostly static. System engineering models defined in SysML are descriptive in nature and do not directly produce analytical results [24], nor are they executable [13]. Different tool vendors provide extensions or their own analytical capabilities that solve SysML parametric diagram [11]. Since the parametric relationships are solved as a system of equations, the analytical model is limited to simple equations. To be able to use more sophisticated engineering analyses, external analysis tools need to be connected to SysML models. Other research efforts are attempting to leverage other standard modeling languages such as Modelica that have a broad range of analytical support through integration between SysML and the Modelica [31]. Domain Specific Modeling environments (e.g., Simulink for control systems) often have richer semantics (e.g., structure, behavioral and sometimes temporal) to support dynamic analyses, simulation and some have formal method analysis and automated test generation [9], [33]. Other approaches provide process integration and design optimization framework allowing for many available analysis solvers or custom solvers for all type of analysis with simulation and workflow automation [26].

There are many options available to us; this is not an exhaustive list and the specific modeling language and tool(s) for the Vision model has not yet been decided. The “As Is” process and SETR artifact dependencies and relationships are being modeled using CORE, as discussed in Section 4.5. The CORE tool was created before SysML, and CORE supports a number of commonly used SE modeling diagrams sequence, activity, N2, and Enhanced Function Flow Block Diagram, and increasingly many of the diagrams supported in SysML tools. Because SysML is general, there are possible mappings to many types of modeling languages (as is true for UML too) [38] as well as support for programmatic interchange based on the XMI standard. This may rationalize why some organizations are using SysML as an integrating framework, that is, they may not be modeling in SysML, but they are using SysML (and

associated tooling) as a mapping or an interchange medium between different modeling languages and environments. While the SysML and UML languages and tools help significantly to formalize the expression, exchange, and graphical representation of system models, they remain ambiguous and in need of extensions to capture the specific semantics of a given engineering domain [34].

Therefore, our team will use modeling notations like SysML in this report. However, the perspectives cited in this section reflect on why the Vision must go beyond and use other more semantically rich and precise model representations, as well as supporting semantically consistent model (digital) interchange between different simulation and analysis tools. Our efforts planned for Phase II involve a modest demonstration, and we fully envision that we'll need to use other modeling approaches that support simulation, analysis, synthesis and generation.

4.3 STRAW MAN

During the kickoff meeting, it was decided that we would attempt to build a model of the Vision. Therefore following good modeling guidelines, we started with a context-level representation that was derived from Integrated Warfighter Capability (IWC) graphic associated with Task 3 shown in Figure 1. The top level IWC is represented using a SysML Block Definition Diagram (BDD) diagram as shown in Figure 11. This provided a way to reflect that the effort involves characterizing all types of information that is necessary to design, verify, validate, produce, acquire and deploy a weapon system. We used other documents describing the Operational Concept Document of Navy Integration and Interoperability (I&I) Environment [29] and created a similar diagram as shown in Figure 12. Regardless of the content and modeling approach (SysML), the mere existence of these examples stimulated significant discussion at the working session and clarified for the team what is meant by modeling the Vision and the concept of capturing all information in “system” model.

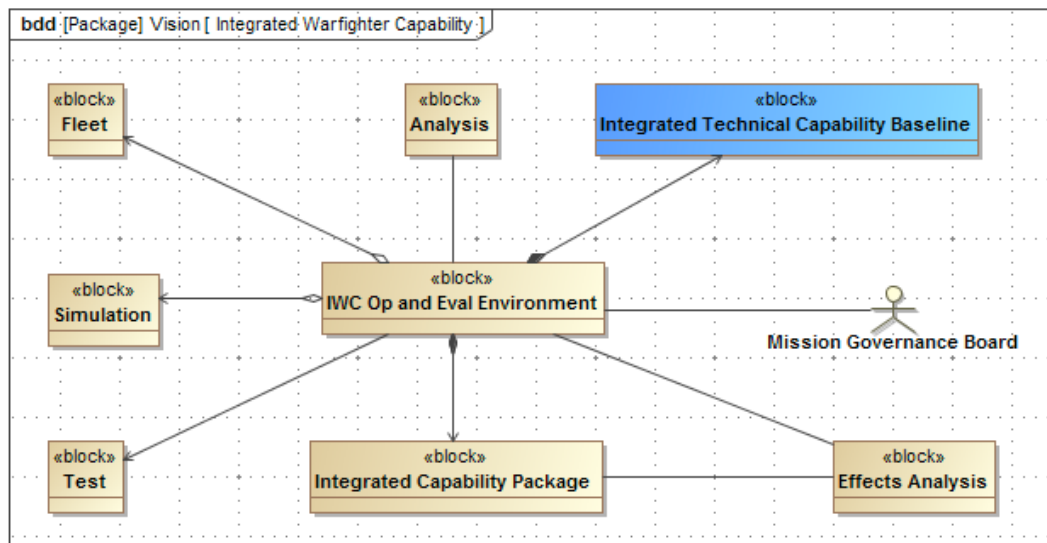


Figure 11. SysML Context of IWC Vision

Conceptually, the Vision model will be a reference architecture (or metamodel) of a multi-level, multi-domain integrated engineering approach to support the IWC. It is not going to describe a specific instance of a system; instead it will ideally characterize all of the types of information related to the design including characterizations of the supporting environmental resources for simulation and analyses, design parameters and constraints, verification and flight readiness evidence, and associated

risk-based signoffs. Ultimately, it should include everything to the Bill of Material (BOM) required to manufacture and produce the system (or in the future the specifications for 3D printing).

It was decided to scope the effort at a Program of Record (POR) (e.g., F18 with weapons, CH-53). Referring to the BDD in Figure 11 and Figure 12, a POR relates to the Integrated Capability Technical Baseline (ICTB) block. The ICTB block is also represented in Figure 11 (the Integrated Warfighter Capability BDD). From the perspective of the I&I Environment BDD, relationships from the ICTB block to the Mission Technical Baseline (essentially where the requirements for the ICTB are derived), and System/Program Technical Baseline blocks are reflected. All of these blocks relate to the I&I Repository. The I&I Repository is part of the Navy's Integration and Interoperability Integrated Capability Framework vision that includes an enterprise data environment for storing and sharing DoDAF architecture and other supporting I&I data in a common format with common ontologies to support cross-correlation and alignment [29]. These BDDs provide two perspectives on the relationships to the ICTB within the NAVAIR vision, but this is still at a very high level. In order to complete a representation of the Vision it will be necessary to formalize:

- All information as typed data elements, which can be represented as attributes in a model
- Data flows reflecting the data dependencies between blocks
 - BDD diagrams often have associated Internal Block Diagrams (IBD), which show hierarchically lower-level diagrams with the corresponding data flow between the lower-level blocks
 - As another type of example, Figure 13 shows that the Vision must not only be able to characterize the elements of the vehicle system, but should also characterize the elements within the overarching environment that show uses or dependencies to resources such as simulation, test environment, instrumentation and logging
 - Surrogates would also be represented by blocks
- Control flow reflecting both sequential and concurrent flows
 - Activity diagrams in SysML can represent both control flow, and the associated data flows that would be associated with flows within an Internal Block Diagram (IBD)

There are other behavioral views (e.g., sequence and state diagrams) and constraint views (parametrics) that would be necessary to fully characterize the information needed to produce an air vehicle system.

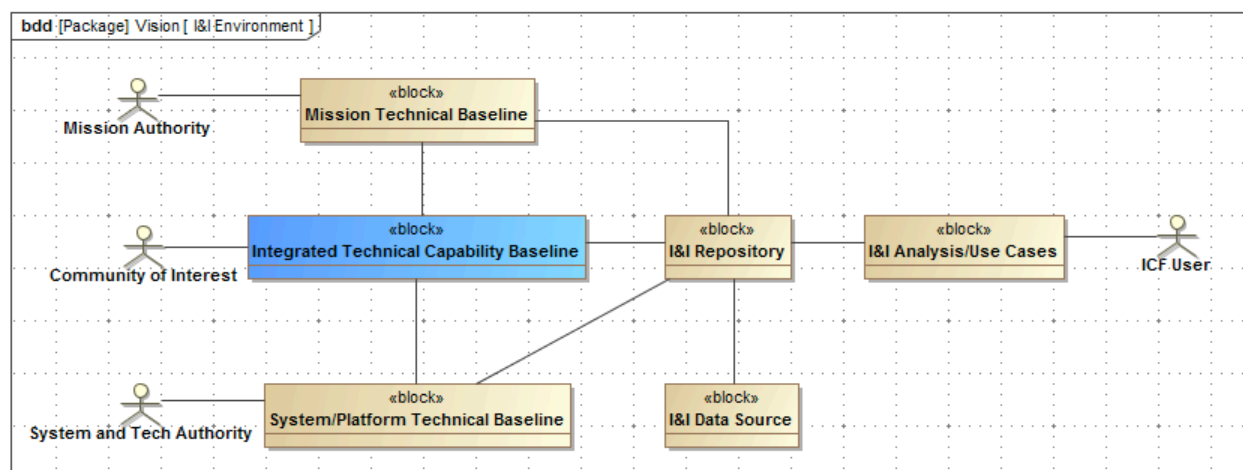


Figure 12. I & I Environment

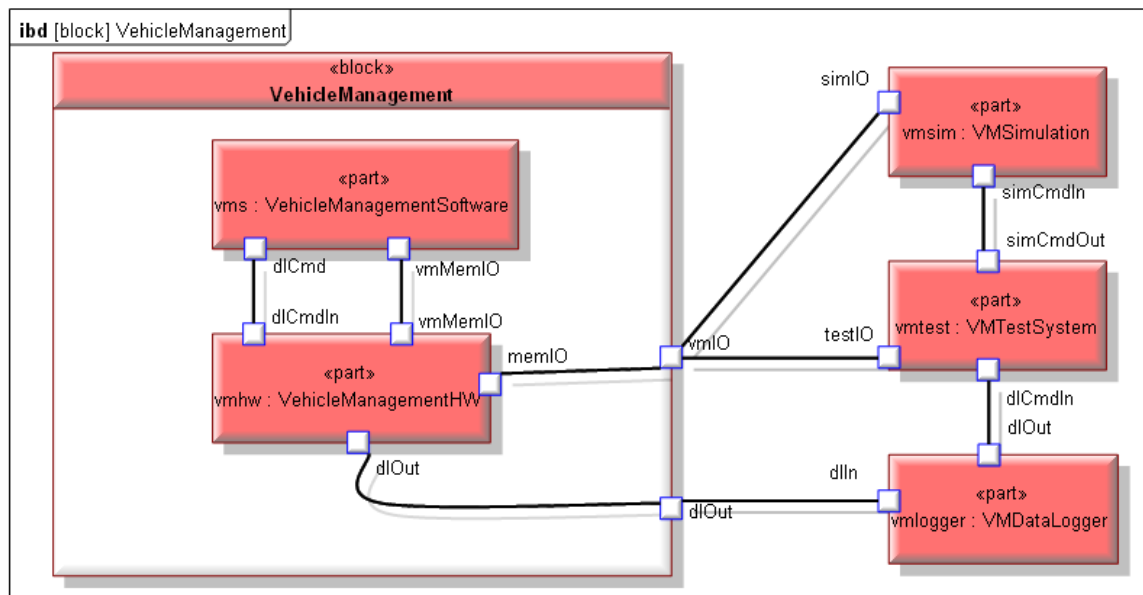


Figure 13. Vision Model Interface to Simulation and Test Resources

4.4 ACQUISITION GUIDANCE MODEL (AGM) MODEL

We also discussed how some aspects of the Vision could possibly be done from a process perspective using other modeling techniques such as Business Process Modeling Notation (BPMN). This is when the MITRE Acquisition Guidance Model (AGM) model effort was identified as a possible contributor to our effort.

In alignment with goals for Task 1, we will continue to investigate, and leverage existing ideas and advances to MBSE through discussions with industry organizations. MITRE developed the AGM [15]. The artifacts and model representation aligns with the DoD 5000.02 phases, and embeds guidance described in the Defense Acquisition Guidebook (DAG), with particular emphasis on Chapter 4 of the DAG, and the relationships between SE guidance [18]. We wanted to determine if we could leverage it to create or map to the Vision model. At worst we should be able to use the AGM to understand the completeness of the “As Is” process as we develop a Vision. This would help people understand how a process would work when transitioning from a document-centric operational model to a model-centric approach.

The AGM was developed using the iGrafx⁶ tool with BPMN [12]. The AGM provides a high-level characterization of the activities, events and messages using a BPMN notation as shown in Figure 14. It provides a time-sequenced perspective on the process using swim lanes to more easily understand the different functional capabilities or responsibilities; specifically it documents activities, messages, and products. The AGM provides a mechanism to examine how SE fits into of range of actions within an acquisition program, how SE leverages results of other acquisition activities and which SE products support acquisition decisions. Some SMEs from organizations such as Defense Acquisition University (DAU) instructors, as well as program managers from Acquisition Category (ACAT) 1 programs have reviewed the AGM. While this could be useful as a completeness check, it is general and the generic artifacts don’t map very granularly to the actual artifacts that NAVAIR must produce from both a functional and airworthiness, safety, and program execution (see Section 4.5).

⁶ We make no claims about this particular modeling tool. It is a tools used by MITRE.

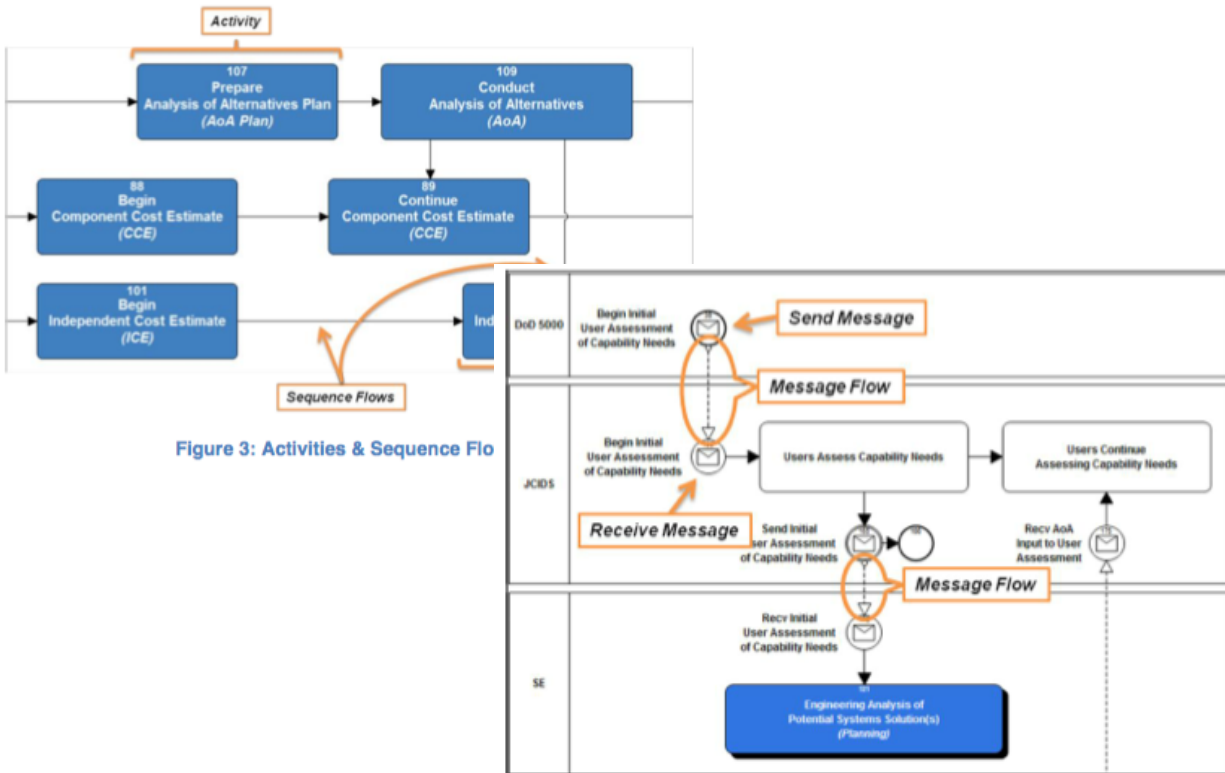


Figure 14. AGM Representations

4.5 “As Is” ARTIFACT ANALYSIS

A key guideline for the SE process is the SETR process. As reflected in Figure 15, the SETR handbook is one of the guiding instruments for the SETR process. It characterizes the **Roles** of the individuals that must perform **Activities** to develop the **Artifacts** that result in **Measures** to make the decisions.

An approach that we used in the past when assisting organizations in adopting MBSE is to examine all of the required artifacts that are produced in their current processes, and then examine the ways models and the associated model-based automation (e.g., simulation, analysis, synthesis, generation, test generation, etc.) can be applied to those models to reduce or eliminate “paper-based” documentation and/or modify or eliminate the manual processes [8]. We have heard similar stories from some of the industry organizations in our preliminary discussions about using a combined bottom-up and top-down approach to transform their MBSE efforts, and are expecting to be briefed on details once we have the appropriate confidentiality/proprietary agreements in place.

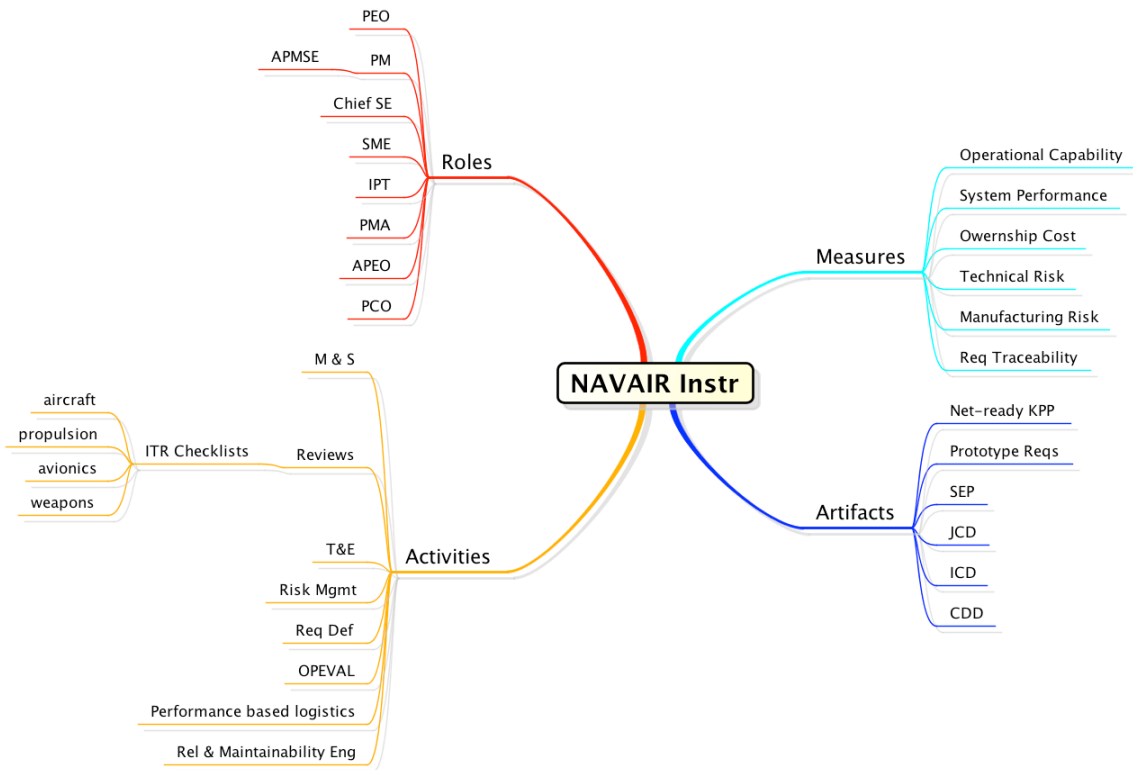


Figure 15. System Engineering Technical Review Process Handbook

Our NAVAIR team categorized about 330 artifacts, which has been reduced to about 140 that are produced as part of the SETR process, as shown in Table 3. The list of artifacts was originally captured in a categorized spreadsheet, however this representation has some limitations, as it was difficult to characterize artifact dependencies and relationship, as well as the timing in the process where they are created or used in reviews. Therefore our team partners developed a CORE model using a data-driven approach to characterize a subset of some of the artifacts (captured in spreadsheet). The concept demonstrates how the data-driven approach allows the inherent process to be derived from the artifact relationships and data dependencies. The CORE tool has different types of graphical views that render different type of relationships (e.g., data flow, data dependency) automatically from information collected in a data-driven way. Two different examples are shown in Figure 16 and Figure 17. NOTE: this is not the NAVAIR process, rather this is just a derived process that relates to the inherent artifact relationships. As reflected in Figure 10, they are also overlaying a process based on International Organization for Standardization (ISO) 15288, also with a mapping back to DoD 5000.02. ISO-15288, published by ISO, is a world-wide standard for systems and software engineering lifecycle processes.

Table 3. "As Is" Artifacts

SE Participation	Activities	Product	Tools used	Model Types	Analysis	Simulation	Generation	Test Generation
High	1- Design (Software)	Software Design Description						
High	1- Design (Software)	Software Interface Design Description (SIDD)						
High	1- Design (Software)	Software Product Baseline						
High	1- Design (Software)	Software Build Plan						
High	1- Design (Software)	Software Architecture Description (SAD)						
High	1- Design (Software)	Software Code Documentation						
High	1- Design (Software)	Software Measures						
High	1- Design (System)	Air Vehicle Specification	DOORS					
High	1- Design (System)	Engineering Drawings	varies					
High	1- Design (System)	Flight Control Detailed Design Report	Simulink, Stateflow	Control Laws	Satisfiability	Matlab	Code	Sim and Code
High	1- Design (System)	Integrated Architecture Model - 1 Requirements Analysis Viewpoints	DoDAF					
High	1- Design (System)	Integrated Architecture Model - 2 Functional Analysis Viewpoints (OV-3,	DoDAF					
High	1- Design (System)	Integrated Architecture Model - 3 Allocation Baseline	DoDAF					
High	1- Design (System)	Integrated Architecture Model (IAM) (DoDAF)	DoDAF					
High	1- Design (System)	Modeling and Simulation Report	Varies					
High	1- Design (System)	Sub-System Design Documentation						
High	1- Design (System)	System Design Documentation (SDD)						
High	1- Design (System)	System Design Specification (SDS)	DOORS					
High	1- Design (System)	System Specification (SS)	DOORS					
High	1- Design (System)	Sub-System Design Description & Analysis Report						
High	1- Design (System)	Sub-System Specification Documentation						
High	1- Design (System)	Training System Functional Description (TSFD)						
High	1- Requirements	Concept of Operations (CONOPS)						
High	1- Requirements	Design Reference Mission Profile						
High	1- Requirements (System)	Software Requirements Description (SRD)	DOORS					
High	1- Requirements (System)	Software Requirements Specification (SRS)	DOORS					
High	1- Requirements (System)	Software Requirements Traceability Matrix						
High	1- Requirements (System)	Net-Ready Key Performance Parameters (NR-KPP)	RSA (?)					
High	1- Requirements (System)	Requirements Traceability Matrix/Product (RTM)						
High	1- Requirements (System)	Requirements Verification Traceability Matrix (RVTM)						
High	1- Requirements (System)	Capabilities Development Document (CDD)						
High	1- Requirements (System)	Capabilities Production Document (CPD)						
High	1- Requirements (System)	Contractor System Specification (SS)						
High	1-Design (System Safety)	System Hazard Analysis						
High	1-Design (System Safety)	Critical Safety Item (CSI)						
High	1-Design (System Safety)	Critical Safety Item(CSI)/Critical Application Item (CAI) Management Plan						
High	1-SE Mgmt	System Engineering Management Plan (SEMP)						
High	1-SE Mgmt	System Engineering Plan (SEP)						

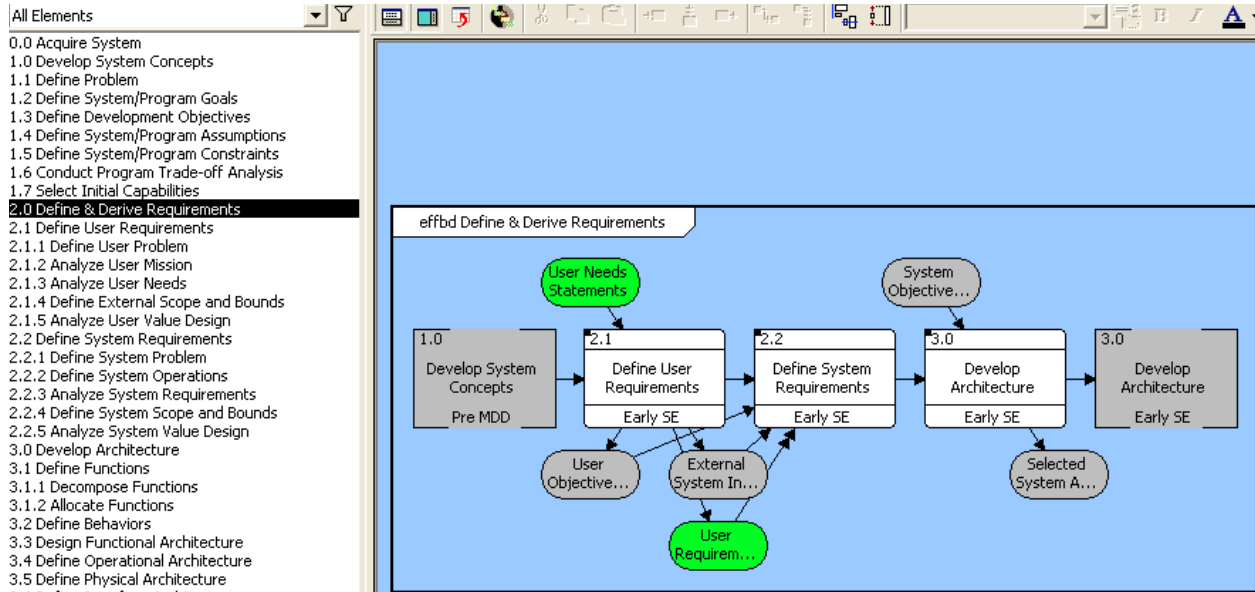


Figure 16. Derived Process

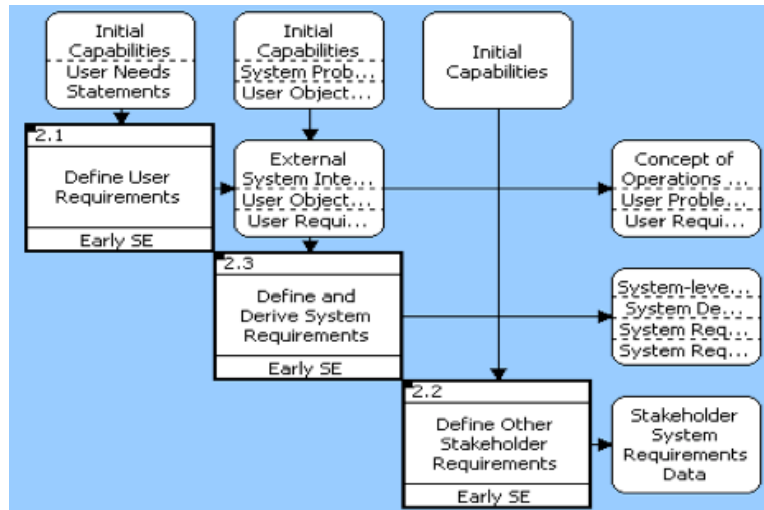


Figure 17. "As Is" Artifacts and Process Relationships

We know from discussions with organizations, and at the meetings with MITRE, that organizations often use a combination of top-down and bottom-up as they evolve into a model-driven approach. Organizations tend to roll out the adoption of modeling in a more evolutionary manner. While this is interesting, the research goal is not evolution rather it is to assess the technical feasibility to radically transform SE through MBSE. However, context does matter, because we also need to assess the technical feasibility in terms of the types of systems and airworthiness needs required by NAVAIR; part of this process is exposing areas where there is expert judgment, historical evidence and rules of thumbs that are used in the decision-making process, which needs to be better formalized and embedded in knowledge within the Vision.

4.5.1 MODEL TRANSFORMATION RATHER THAN MODEL EVOLUTION

To reflect on the concept of model transformation rather than model evolution, we provide the following example to describe how model-based automation can completely eliminate manual effort and result in radical transformation of the “As Is” process through an automated workflow. The following provides a scenario for how to think about using models to replace artifacts, and more importantly how model-based automation subsumes manual efforts. Referring to the artifact “Flight Control Detailed Design Report,” which is highlighted in Table 3, this type of artifact would:

- Represent “Control Law” in a model
 - Simulink⁷ and Stateflow are commonly used to model control laws (e.g., F16, F18, F35)
- Automated analysis that exists today, (e.g., it has been applied to F35) would include:
 - Satisfiability: proving that each thread through the model has no contradictions (mathematical consistency)
- Simulation
 - Simulation of Simulink models is often done using Matlab
 - Support high-fidelity simulation using Matlab
 - Support higher fidelity with real-time execution within the surrogate or prototype system implementation or actual hardware though automatic code generation
- Synthesis or generation

⁷ We are not promoting Simulink, we use it as an example, because it is almost a defacto standard for control system modeling and simulation

- Code generation from Simulink models can be provided by Mathworks and other commercial products
- Automatic test generation directly from Simulink models
- Automatic test driver generation
- The test vectors are transformed into various types of test drivers that are run both against a Matlab simulation and the auto-generated code; if all tests pass (the actual output equals the expected output) in both the simulation and generated code execution environments then there is a strong verification argument that the code satisfies the specification
 - Organizations run the test through both the simulation and code, because organizations have been able to find errors in the code generation (Risk reduction argument for using model-based tools)
- Code coverage tools such as LDRA and VectorCast have been used to show that the tests provide Modified Condition/Decision (MC/DC) coverage
 - Code coverage measurement, which provides quantified risk reduction evidence
- The Mathworks code generation uses a particular algorithm that produces code that is “deadlock” free
 - Eliminates concurrency analysis

These are types of model-based automation that leverage models to “Cross the Virtual V.” While this can be, and is commonly done on low-level high-fidelity models, we are also interested in applying this type of concept at the upper-levels of the “V” with varying levels of fidelity that provide integration of model and model automation at different levels of the “V” as reflected Figure 18. This figure is not complete, as there are many lines not included between all of the different types of model, but this diagram has been useful in conversations about “Crossing the Virtual V” during working sessions. These types of models mentioned at the upper-level of this V may not directly relate to the “As Is” artifacts, but they must be defined in the Vision.

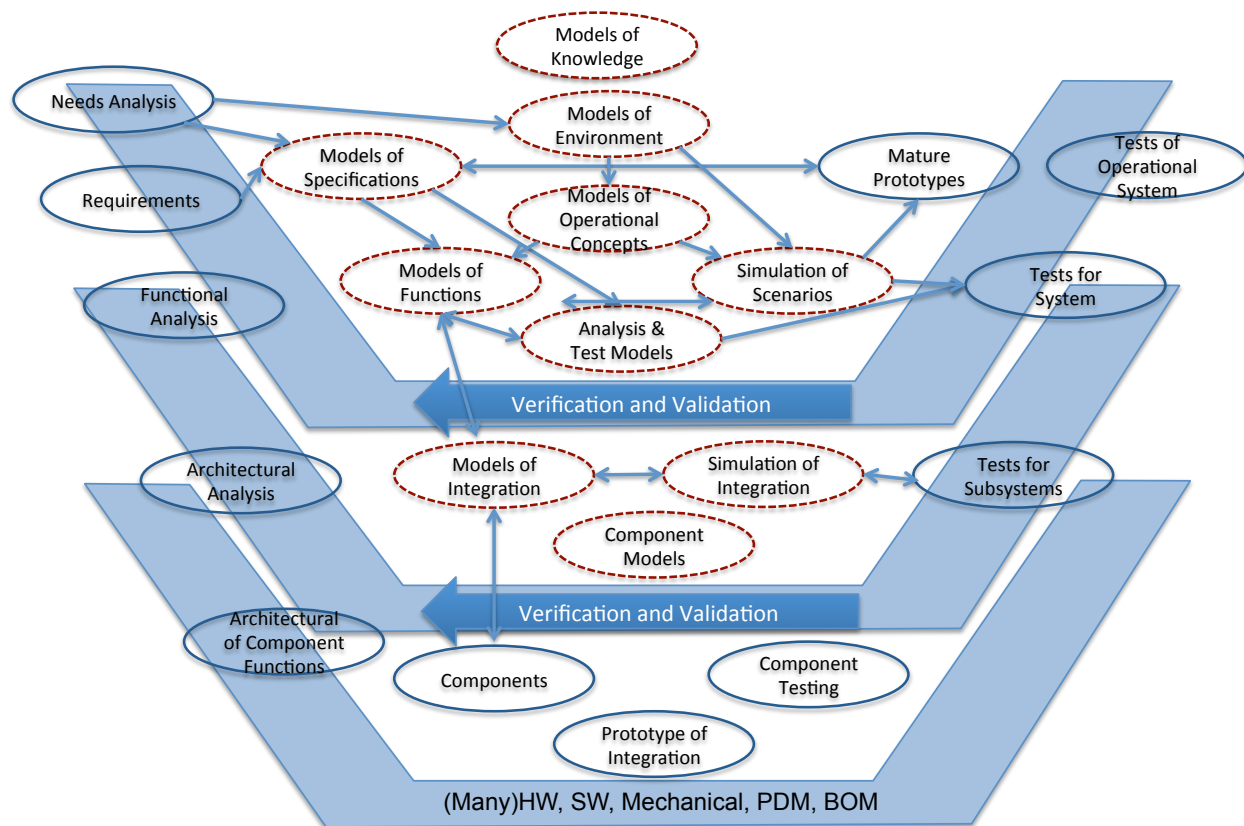


Figure 18. Notional Multi-level Crossing the V

We have continually discussed the notion of “Crossing the Virtual V” as an important way to assess system design concepts in the context of mission scenarios. However, in discussions with organizations, there are some that believe that the notion of a “V” is a historic manifestation of “the” traditional flow of document-driven work, and we should eliminate the use of the “V” as part of systems engineering dogma as it is counterproductive to embracing approaches that support the continuous integration of digital artifacts. The “V” introduces points for disconnects and failure. What’s more critical in the Vision is continuous integration of various types of digital assets, with varying levels of abstraction and various degrees of fidelity. Section 4.5.2 provides some discussion on this point using examples to further clarify the notion of physical surrogates, and support the argument that the “V” may not be a good metaphor.

4.5.2 DIGITAL AND PHYSICAL SURROGATES

The concept of “model everything” relies heavily on digital assets such as physical surrogates, existing system or component re-purposed for new concept exploration and prototyping. Our NAVAIR team created a concept for representing System Level Maturity, as shown in Figure 19. It reflects on the idea that as we are attempting to “Cross the Virtual V” and will rely on physical surrogates, which is commonly done today, both in aerospace and other domains such as auto racing. The actual airframe, shown on the right side of the V matures (top-to-bottom) and the actual aircraft is first flow (e.g., F-35, 15-December-2006) long before many of the complex software intensive systems are developed and integrated, as the aircraft airframe and new materials are being evaluated. Key early capabilities such as software for the control laws to fly the aircraft are often evolved from earlier aircraft systems (e.g., many versions of MATRIXx and/or Simulink models have been evolved for years, and will continue to be evolved for years). Yet, all of these systems are continually refined and as the timeline of system

capabilities mature, new capabilities are added to the system. As the subtitle “integrate and build” suggests, continuous integration is the key to this paradigm. Formalized interfaces are required for integration, and the semantics for the interfaces often need to be formalized: 1) structurally, 2) behaviorally, and 3) temporally, in order to use surrogates and simulations. Document-based specifications do not formalize these, however some modeling approaches can, and with semantic formalization, automated verification can be supported directly from the models.

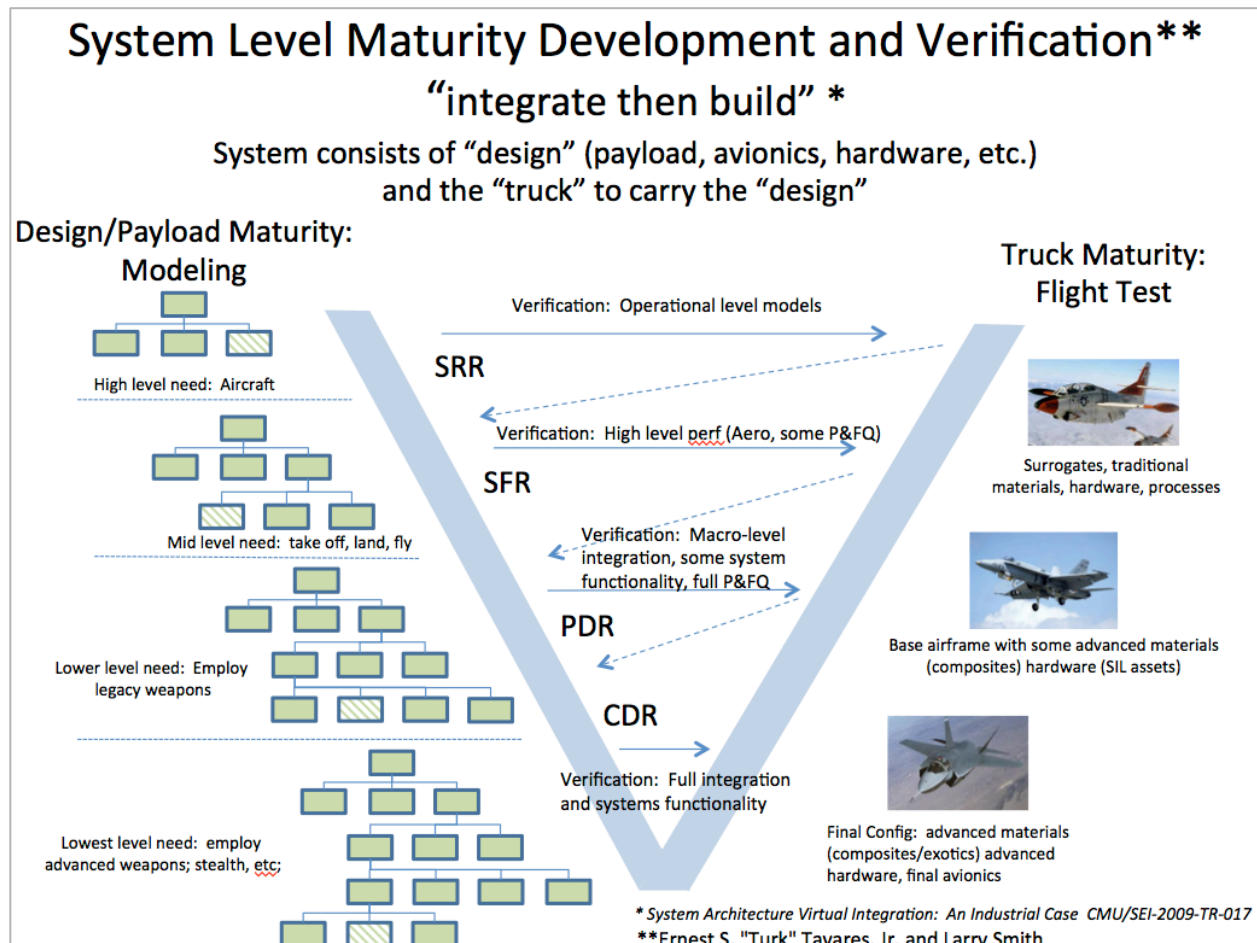
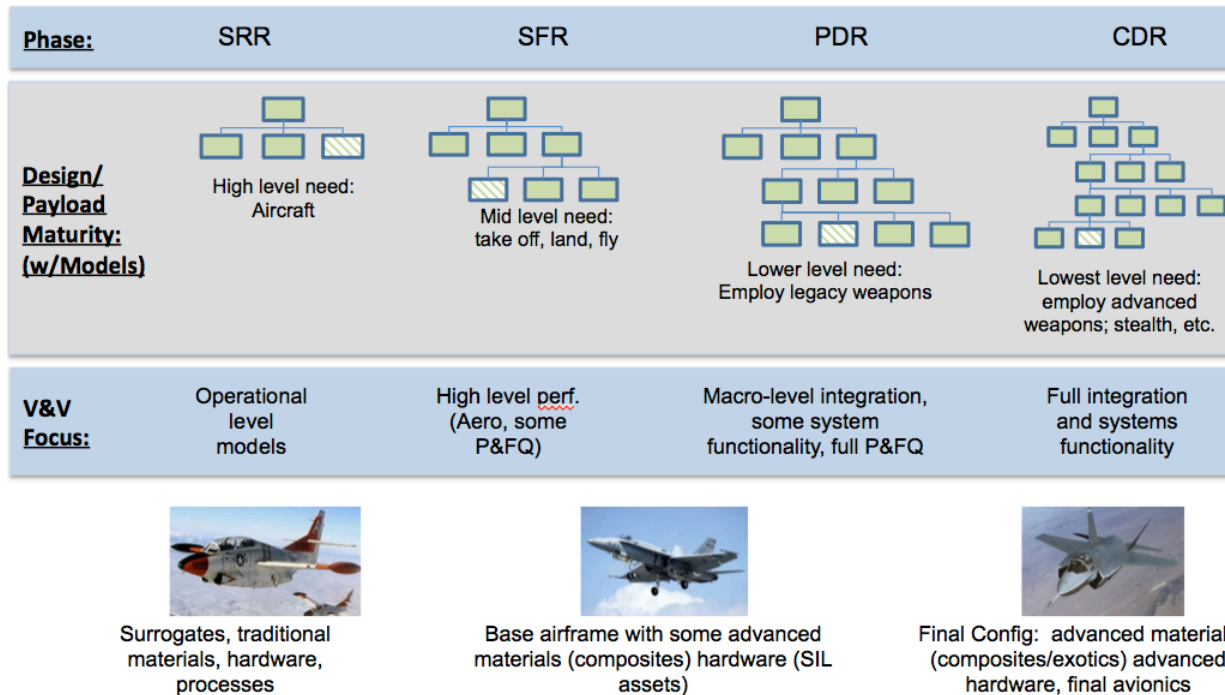


Figure 19. System Level Maturity Representation for Development and Verification

The key issue with the traditional V as shown in Figure 19 is that the V model does imply time progressing chronologically from left-to-right, and while the concept of “Crossing the Virtual V” is notionally easy to understand, and as pointed out by one of our discussion groups, the V model does not work well in a model-based paradigm. Figure 20 presents the same logical progression of the design and verification that is aligned with the traditional lifecycle phases, and progress does correspond with a left-to-right time ordering.



**Derived from Ernest S. "Turk" Tavares, Jr. and Larry Smith

Figure 20. Non-V Model System Level Maturity Representation for Development and Verification

4.5.3 VISION MODEL REFERENCE ARCHITECTURE

Generic processes and guidelines for characterizing requirements, designs, variants, verification evidence and risks using a document-based approach simplifies the way process artifacts are titled or labeled as reflected in Table 3. However, as shown in Figure 21, there are many types of major systems elements, and subsystems within an aircraft system. Therefore, we can image that the model of the Vision must need to use a type of reference architecture in the characterization of an integrated set of model types (software, electrical, hydraulic, human interface, etc.) that represent all of the engineering aspects of an aircraft system (i.e., the "total" system model). There must also be ways to characterize different types of elements, for example, a winged aircraft may not have rotors, and a UAV may not have avionics displays.

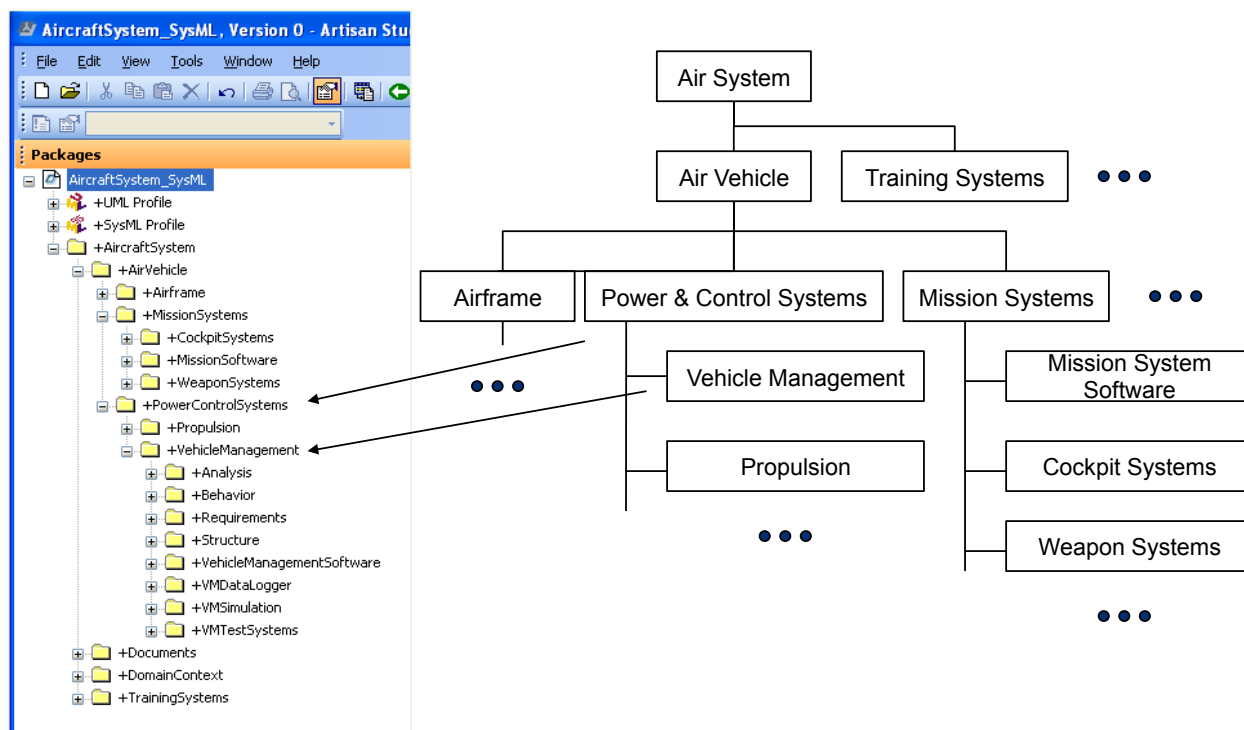


Figure 21. Model Topology Often Mirrors Architecture of System

4.6 SCOPE TO PROGRAM OF RECORD THROUGH DIGITAL CRITICAL DESIGN REVIEW

The scope reduced at the last working session was to focus on the process up to critical design review (CDR), for the “As Is,” and for the Vision model and risk framework for a POR. It was thought that the technical reviews are good “checkpoints” since they focus on different decisions and levels of engineering content that would need to be represented in the models. Only the PDR and CDR are always required. Other reviews ASR, SRR, SFR, TRR, SVR, PRR may or may not be required on a given program. Ideally, we’re looking for a new concept: Digital design from CDR artifacts (DCDR). We want to investigate a more continuous notion of PDR and CDR (or DCRD) where reviews of models and analysis artifacts occur everyday until all of the required evidence is provided in order to support contracts and signoffs.

4.6.1 CONTEXT FOR PROGRAM OF RECORD SYSTEM

Along with discussions with organizations external to NAVAIR, we have had preliminary discussions and are also planning discussions and demonstrations to better understand the context of the current environment in order to more precisely characterize the information that is formalized in the form of models, simulation, and analytical data. The context for the POR starts from environmental aspects at the mission-level. For many efforts organizations often start with an OV-1 diagram of the mission-level with systems-of-system (SoS) level interactions. The operational views decompose the mission within context of the situation, and provide different viewpoints that describe the tasks and activities operational elements, and resource flow exchanges required to conduct operations.

Building on lessons learned creating early DoDAF models, analyses have uncovered that interoperating at the lowest (data) levels is insufficient for scenarios, and scenarios require behaviors; missing at the data level. DoDAF does not accommodate other scenario requirements (e.g., conditions assumptions) very well, and is insufficient to fully characterize the dynamic needed for analysis. This is not surprising,

as DoDAF has mappings to SysML [38], and we have discussed some of the limitation of SysML in Section 4.2, especially related to dynamics of models.

As a result, study views were created to address a number of challenges at this level. A mission-level SoS analysis begins with formalization through Study Views, as reflected in Figure 22. Study views provide structure and a common context that acts as a basis for framing and bounding the functional decomposition of DoDAF products. Study views formalize the need and intent, provide a situational context and influencing factors to frame and bound the functions and activities of the mission and scenarios that ultimately lead into corresponding representations of the Mission and System Capabilities (i.e., the capabilities for the POR). These capability representations are further analyzed using modeling and simulation and corresponding analysis capabilities. The outputs of which are then formalized in terms of DoDAF artifacts. This information will form the analysis boundaries for the System Capabilities information that is to be captured in the Vision model.

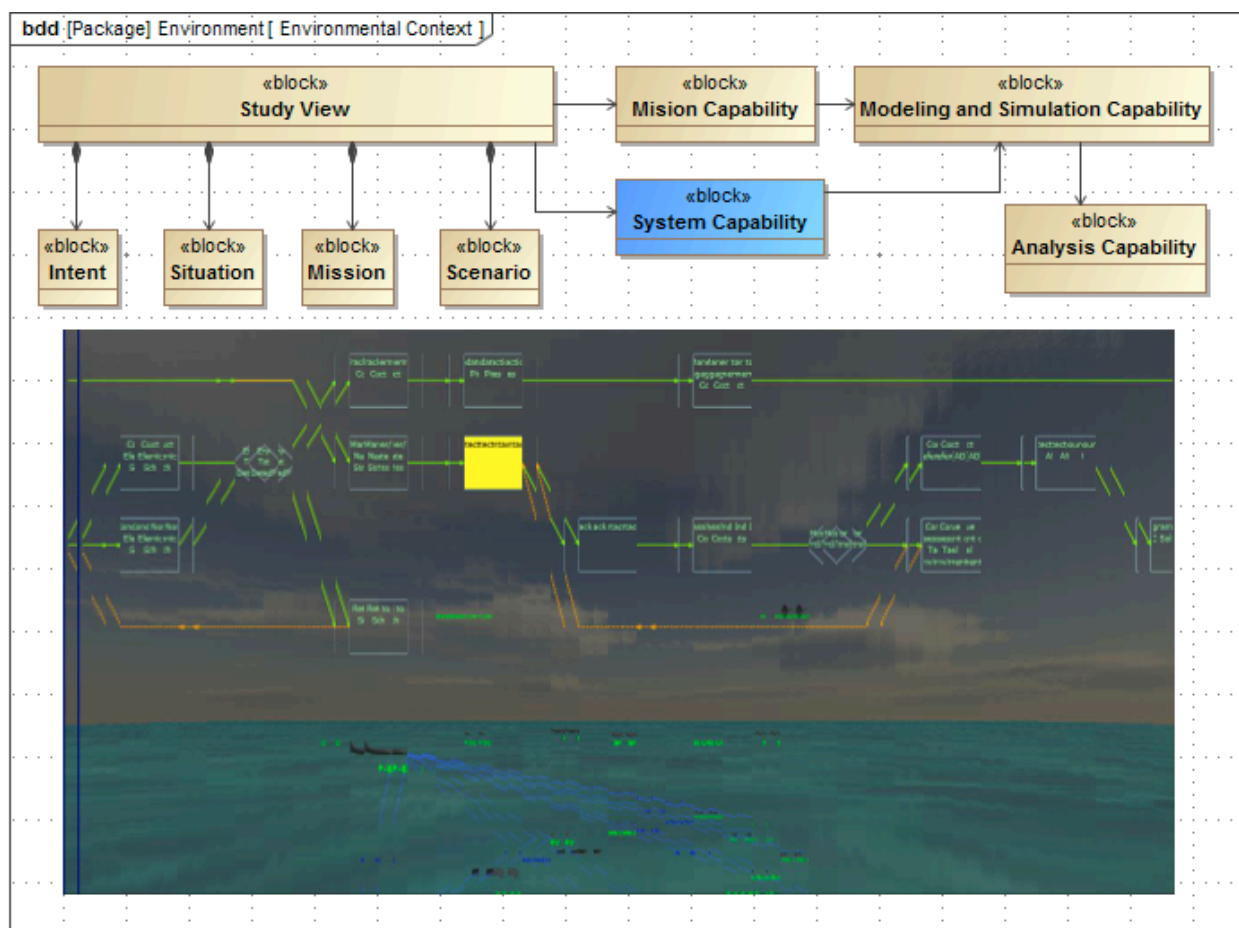


Figure 22. Mission Context for System Capability⁸

4.6.2 CASE STUDIES AND EXISTENCE CASES

We have bounded the scope of this effort. Figure 22 identifies the context level view for the definition of a POR system capability. It does it in the context of a Study View, which is a more abstract view than a DoDAF or SysML characterization. The “As Is” artifacts discussed in Section 4.5, constrained in time to the CDR limits the scope moving to the right as reflected by Figure 21.

⁸ Image source: Thomas Thompson, Enabling Architecture Interoperability Initiative, B210-001D-0051 Unclassified.

We are still in search of a case study. It is desirable to have a case study that can provide technical design, cost, airworthiness and risk data. NAVAIR identified in the final week of this project a possible candidate, but if that information cannot be provided, we will look to develop our own case study example or transform some existence cases [22] into scenarios.

One possible candidate was developed as part of a Simulation Based Acquisition experiment, where a low-fidelity abstract model of an F-35 slow takeoff vertical landing (STOVL) state machine model was integrated with high-fidelity control laws model [7]. This was a virtual representation of system capabilities, where two different models were used to automatically generate simulation code. The models were analyzed using a formal methods tool (i.e., theorem prover), and test vectors were automatically generated to illustrate both the integration of low and high fidelity models, synthesis, simulation, and model-based verification. No airworthiness requirements were applied to this example.

Another possible candidate was demonstrated by a commercial MBSE tool company that we'll be meeting with as part of our Task 1 discussions. This model illustrates a UAV capability to support the mission of aerial artifact camera-based examination (e.g., water-based wind turbines), and demonstrates aspects such as: flight control, flight dynamic, propulsion and energy, and mission execution. This model may be supplied under our confidentiality agreement. This model does not address airworthiness, but could be tailored to support this type of required analysis.

5 TASK 4 – INTEGRATED FRAMEWORK FOR RISK IDENTIFICATION AND MANAGEMENT

We want to investigate the use of risk-based models that align with the Vision to “model everything.” This involves how the Vision should include integrated risk identification and management as reflected in Figure 10. While there are many classes of risks to manage, for NAVAIR there are fundamentally two key classes of risk that must be considered:

- Airworthiness and Safety (most critical in Technical Feasibility assessment)
- Program execution (cost, schedule and performance)

There are also two complementary views of model-based acquisition with respect to risk:

- Risks introduced by modeling deficiencies and risks reduced by enhanced use of modeling
- Modeling to predict or assess risks (i.e., modeling for uncertainty quantification in acquisition and in the use of models)

5.1 PREDICTIVE MODELS FOR RISK

The SERC team has used models in the prediction of risk, and plans to use predictive analytic models to support risk identification and management. More generally we can use models to provide risk quantification for almost all types of decisions that are made by stakeholders (e.g., model-based reviews). As an example, we created a Bayesian model using factors derived from the Airworthiness standard MIL-HDBK-516B [20] as shown in Figure 23. This is conceptually similar to the approach we are using on an FAA NextGen research task for collaborative risk-informed decision-making [4][5][6]. The key characteristics of the approach are they ensure that all factors are considered in the decision-making process, and that all classes of stakeholders are adequately represented in the decision making process. A systematic and comprehensive treatment of all relevant factors provides better risk identification.

We used this model and an example from a true story related to a C130 Weapon Delivery system to illustrate the concept. While this model is notional at this time, this example started a discussion with the team about how stochastic (probabilistic) models can play an important part of the Vision as they formalize many aspects of the human decision making process that will be important at many gates, reviews, and decision points of the Vision concept. Each factor covers a specific aspect of airworthiness, to ensure that all possible uncertainties and risk are considered in the quantification of risk. The risk index is a probability distribution, where for example, the mean can map to quantities in a risk matrix.

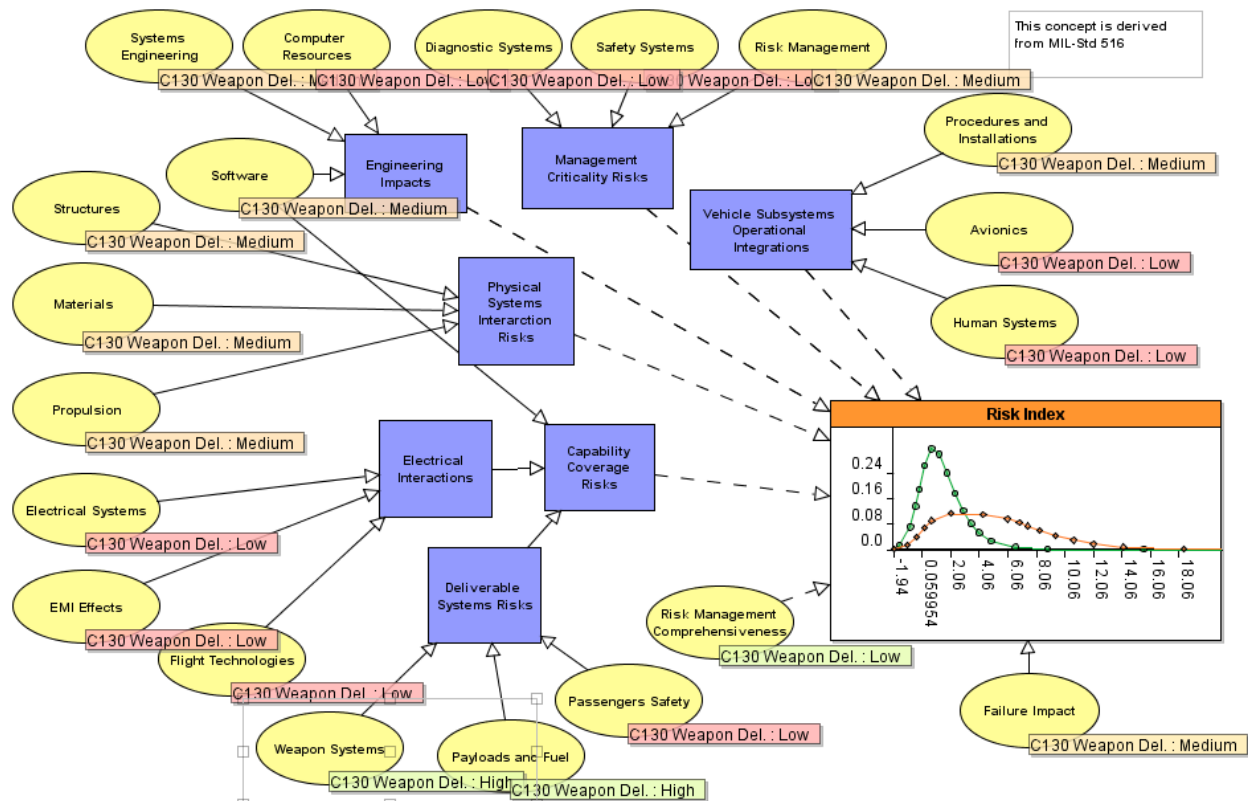


Figure 23. Bayesian Model Derived from Airworthiness Factors

5.2 RISK FRAMEWORK APPROACH TO UNCERTAINTY QUANTIFICATION MODELING AND PREDICTION

The SERC team has also been working with NAVSEA to develop a framework and approach to Uncertainty Quantification modeling and prediction. The approach has three main components:

- Identifying the design, test and modeling factors at different system scales
- Analyzing the uncertainty, variability, and error in design implementation, testing, and modeling
- Using experimental design methods to assess the contributions and interactions to system (airworthiness and safety) and program execution risks

The risk modeling and analysis approach also addresses potential errors and uncertainties in the overuse of limited data. Ideally:

- One data set is used to identify critical factors
- A second independent data set is used to develop the models
- A third independent data set is used to calibrate the models
- A fourth independent data set is used to assess the expected error in model results

In practice data sets, surrogate vehicle test data, etc. are limited. Bootstrap methods use repeated resampling of the data and repeating the modeling and analysis process to obtain a statistical estimate of the uncertainty in model-based acquisition given the available data. Further analysis reveals the value – reduction in uncertainty – for additional data.

These types of models capture and embed knowledge associated with expert judgment, historical evidence and rules of thumbs that are used in the decision-making process.

5.3 SCOPE OF THE RISK FRAMEWORK

We worked with our NAVAIR team members to determine the scope for the risk framework. Key to the representation of the models (and Task 3) to support risk identification and management is to **characterize the types of evidence that are required for Flight clearance and Flight readiness**. It is important to understand how the models are developed and derived in order to understand the risk strategies that must be in place for assessing the evidence for flight clearance.

The process for risk under consideration for this SE transformation covers system development from Milestone A to CDR (at least for now). These questions related to risk also helped to refine the scope for Task 3, and introduced a new term Digital CDR (DCDR), with a heavy emphasis on **digitally-derived evidence for airworthiness and safety, but to also include program execution**.

In both preliminary discussions with organizations and our NAVAIR team, it is recognized that it is important to quantify “margins” and “sensitivities” as a way to quantify risk.

As an example, one of the organizations (in our preliminary Task 1 discussion) creates new types of advanced material for a system. They cited a particular effort working with advances in new material and processes at the nanoscale. At the component level the margins seemed acceptable. However after composing the components, margins propagated to unacceptable levels in the final integrated form.

Risk implies probabilities of what might go wrong or might not happen (on time or due to the degree expected), and some distribution of magnitude of consequences. This requires “impossible certainty” of the degree of uncertainty and advance knowledge of the likelihood and effects of unidentified events and factors. Therefore, we suggested that a better framework might be to work in terms of design margin. Design margin is more closely related to design. Design margin is how much room there is for a subsystem or component to perform less well than expected or to have greater burdens than expected until it becomes a problem. In some cases, e.g. weight, any increase adds to total weight, so instead of a weight margin, we might want to think in terms of sensitivities (sensitivity in increase in total weight, time, cost, etc. to a percentage increase in the component weight, time, power draw, etc.). This creates a number of questions for this task, for example:

- Can we use models to see how much design margin there is in a system – specifically when we cannot push the system to failure; which types of models and how can we use them to estimate the conditions under which the system begins to exhibit unstable response
 - In control systems analysis this is often taken to be the 3dB point – the frequency of input variation at which the output-to-input ratio is half what it was for low frequency change, or the 90-degree phase-shift point, where the frequency of input variation at which the system response lags by 90 degrees
 - Control systems analysis methods also address the acceleration, velocity and displacement limits at which the system dynamics change
 - Failures are often associated with transitions from linear to highly non-linear regimes; often the structure, interactions and/or dynamics change in these regions (e.g., insulators or isolators fail, etc.) – e.g., the acceleration, velocity and displacement limits at which the system transitions from linear to non-linear response
 - Models that are relevant in the “linear” regime will give erroneous results in the non-linear regime
 - Models that do not represent the dynamics that change the structure of a system (e.g., insulation wearing off causing a short-circuit, structural failure of a linkage, strain transitions from elastic to plastic deformation, etc.) will give erroneous results

Mechanical or electro-mechanical control and isolation systems are good examples, and important for airworthiness. Control systems work within a limited range. Standard control system analysis examines the frequency response and looks for the 3dB frequency, i.e. the frequency at which the transfer function is half of the low-frequency value (the transfer function is just the ratio of output-to-input). Other limits include maximum displacement, velocity and acceleration – when the system hits hard-stops, current limits etc.

Surrogates can be driven with increasing frequency inputs to find the 3dB point without having to experience the failure. The input parameters of virtual models are often “tuned” to match the 3dB point of test data, and then used to extrapolate to find the 3dB point of hypothetical systems. Physically realistic models can be used to estimate the limiting thresholds of stable response, provided the models and inputs are adequately calibrated and validated. Special consideration is needed for basic physical processes with non-linear response in the regime of operation, e.g., friction between moving parts versus friction between stationary parts.

Nested control loop models have been used effectively in system safety modeling and analysis [27]. The outer control loops detect changes in the response behavior of inner control loops, and then adjust the parameters of the inner control loops to bring the inner loops back into the stable regime. The SERC team has used this framework to model driving behavior and system response at the “safety limits.”

In the use of modeling and simulation, there are different types of simulation with different levels of fidelity. A significant challenge is that tools don’t often map well to different levels of abstractions. These are areas to frame risk. There are increasing uses of model transformation from one level or to different disciplines. Model transformation and model consistency between these views becomes a risk issue.

A companion concept is credibility of the estimates of performance, cost, etc. High credibility if it has worked in a surrogate system, less if it is similar to something demonstrated in a surrogate and model extrapolation. It will be important to better understand model extrapolations.

- Less credibility the farther the model extrapolation is extended
- Less credibility going from surrogate system to bench testing, etc.
- Use of multi-scale calibration and validation
- Use of progressive model-based design confirmation in technical reviews
 - Subsystems mature and are integrated at different rates
 - Sometimes early decisions are needed for long-lead time items whose specifications can be confirmed before other aspects of the system (e.g., final control system parameter values)

5.4 RISK FRAMEWORK CAPTURES KNOWLEDGE

These types of risk frameworks are actually knowledge models of credibility (not models of performance, but models of uncertainty). Part of the effort on modeling the “As Is” process (Task 3) is to identify and then formalize within the models the information and associated knowledge for evidence-based decisions and evidence-based timing of decisions. Other considerations and opportunities:

- In the “As Is” process, what decisions are artifacts of the process, but not essential to the engineering development?
- Are there lost opportunities by making early concept and design decisions?
- Is there a risk of bad decisions, risks and costs of no or deferred decisions, during planning, or during execution?

- Reconsider the “full system” technical review model. Not all parts of the system are ready for PDR, CDR at the same time. Some are more mature than others. Maybe a granular approach is needed.

The timing of technical reviews and decisions should be made when there is an accumulation of evidence sufficient to make a credible decision. Ideally, this will be inherent in the Vision concept, when the required information and associated analyses are complete, the evidence and timing for decisions should be triggered events in the automated workflow.

5.5 RISK RELATED RESEARCH

SERC research teams are involved in several related research efforts that will be leveraged in the risk framework. We need to explore how the following can be leveraged:

- The High Performance Computing Modernization (HPCM) CREATE program to use high-fidelity models in systems design is establishing a working group on Uncertainty Quantification. SERC partners are collaborating with NAVSEA and the HPCM program.
- The DARPA internet-fabrication (iFab) project sponsored research by a SERC collaborator to develop software to automatically detect and complete gaps in specifications for a “build to” design.
- The US Army TARDEC is developing knowledge models to capture design factors and relationships in system design and development. The resulting decision breakdown structure and process should help distinguish substantive design and engineering decisions versus artifacts of the “As Is” process. SERC partners are coordinating with this effort.
- OSD is sponsoring a SERC project in “risk leading indicators” and “risk estimating relationships,” analyzing the consistency, completeness, and complexity of the system architecture, requirements, task structure, and team organization, and combining those with TRL/IRL levels and Advancement Degree of Difficulty indicators (this project is being conducted in collaboration with TARDEC and an acquisition program).
- The Engineered Resilient Systems (ERS) effort is addressing lost opportunity by making early concept & design decisions, the time and cost to reverse decisions, and tradeoffs between timely but bad decisions versus deferred decisions. SERC partners are collaborating with the NAVSEA ERS and set-based design projects.

5.6 RISK OF SE TRANSFORMATION TO MBSE

There is also a concern that the risk of SE transformation to MBSE will fail to provide an efficient, effective and reliable alternative to the current process. There are currently no good ways to assess if a new MBSE approach produces outcomes as good or better than the current process. Regardless, it will be important to establish Measures of Effectiveness (MOEs) or Measures of Performance (MOPs). However, this effort still remains focused on assessing the technical feasibility, and not the adoption of MBSE.

6 CONCLUSION AND NEXT STEPS

This research supports the SERC's research thrust for SE Transformation, where the goal is to move from engineering approaches for systems designed for optimal performance against a static set of requirements over long procurement cycles to approaches that enhance the productivity of engineers to rapidly develop cost effective, flexible, agile systems that can respond to evolving threats and mission needs.

In our preliminary discussions with organizations in assessing the state-of-the-art in MBSE, we see a general trend towards more widespread adoption of MBSE, rather than the radical transformation desired of the NAVAIR vision. Our measurement instrument will continue to be refined in order to characterize those types of enabling technologies, methods and innovations that result in such a radical transformation.

As we move to Phase II, we are looking for existence proofs in example uses of MBSE. We will develop case studies as we focus on the objective for Tasks 3 and Task 4 in order to develop a modest demonstration. We will continue to develop an approach to map the "As Is" process to the Vision, which should help provide confidence about the completeness of the Vision and ensure that we deal with the critical requirements of safety and airworthiness.

The representation for the Vision is more of a reference architecture of the possible types of program data that are captured; there will be a need to have dependencies/constraints as different types of data are captured and needed depending for example based on: land-based, sea-based, etc. We will refine the Vision and link/map to existing documentation, until the attributes associated with the data are formalized in the Vision model. We will use case study data to scope the problem, use and mine historical data from programs of record. This should include how to capture and represent other aspects such as airworthiness constraints, affordability data, earned value data, and risk examples. Many key distinguishing characteristics of the vision will revolve around more integration, interoperability and interaction with the modeling and simulation world. We will represent where and how models are used to produce model artifacts that were typically captured and reviewed as documents.

We are working with our NAVAIR consultants who are characterizing what a "Contractor" could use as model-based requirements and design constraints with respect to this Vision concept. This includes what would be used at a Digital CDR in order to provide the needed information and evidence for the decision gates represented as models or digital artifacts in order to support risk-based signoff.

We are still in need of case study data, and we would like to better understand the inventory of simulation assets used by NAVAIR. We will use case study data to look at the various gates from a historical point of view to understand the data required for decisions represented in the formal of digital evidence.

The specific efforts for Phase II will include:

- Continue to conduct and analyze the results from discussions with Government, Industry and Academia, along with refinement of the collection and measurement instruments
- Evolution of the model lexicon, and continuous updates to a website
- Model of the "As Is" and mapping to model of the "Vision" with traceability and completeness analysis to the DoD 5000.02

- Risk management framework that aligns with the “Vision”; this can include examples such as the Airworthiness risk model, risk factor analysis from case study data and/or program execution risk models
- Demonstration thread(s) based on case study or surrogate data; we will either use case study data provided to us, or we will create some type of surrogate case study

Factor Definitions

The following is the current set (fifth version) of the set of factors associated with the discussion measurement instrument (see Section 2). As the discussions with organizations are held, these factors and the associated categories will be refined.

Table 4. Discussion Instrument Factor Definition

Factor Category	Factors	<u>General</u> These factors relate to the degree to which advance MBSE provides a holistic approach to SE	Commentary
Magnitude of applicability over the lifecycle	Organizational Scope	What is the scope of the MBSE usage? Normally, when thinking about NAVAIR systems the scope is quite large and involves large programs. Therefore, what organizational scope does the MBSE usages apply: Program, Project, an entire Business Unit, Platform (e.g., a type of a specific aircraft, tank, automobile), Department, or Site.	Key to all of these questions is that we are looking for "Technical Feasibility of "doing everything with model." We recognize that actual adoption can be difficult, and might not make sense on older systems. Therefore related to this, it is probably best to ensure that the question perspectives come from a Chief Engineer, Chief Technical Offer, MBSE Organizational Specialist and possibly the Program Manager. To carry this a step further, it might also be important to keep the "systems" perspective in mind, because some of the concepts discussed may have been applied in Hardware and possibly in Software (e.g., the control laws for the F35 are built in Simulink, with auto code generation, and a significant portion of auto test generation), but not completely at the Systems level.
	Scope Impact	How broadly does the answers cover the entire lifecycle (for example, a university research project might be very advanced in terms of analysis or simulation, but it does not cover the entire DoD 5000 lifecycle).	The answer to this question has a lot of weight, because we need to consider answer in context of lifecycle applicable to NAVAIR (and in general DoD Acq. Programs).
Proven beyond a research concept	Demonstrations	Are the capabilities discussed actually in operations - have they been demonstrated?	We want to understand that things discussed are more than just research concepts.
Crossing the Virtual V	Integrated Simulation	In order to Cross the Virtual V, there will be many types of modeling and simulation required to support various type of domains within the system. To what degree are the simulations integrated, and better yet do different simulations work off of shared models?	In order to "cross the virtual V" during the early stages of development, it is important to understand if the inputs/outputs from one set of simulations can feed another (e.g., to be able to understand the capability in the mission context)
	Formal Analysis	Are the analyses (e.g., property analysis) formal, meaning that they are performed on models automatically?	Is the analysis fully automated from the models (H) or is there human interpretation required (M or L) or none (L)?

	Domain Specific	Are the different types of models related to the domain? For example, control system engineers often use Simulink/Matlab. Also, most modeling and simulation environments are domain-specific.	Domain-specific modeling languages are an emerging trend; these types of approaches provide intuitive abstractions (often graphical) that are familiar to engineers within the domain. Rather, SysML, while good for systems engineers, it might not be applicable to flight controls, networks, fluid dynamics, etc. In addition, there is not significant support for automated V&V from SysML as the semantics are not very rich.
Cross Domain Coverage	Domain Interoperability	Are the models that are in different, but related domains integrated? Are the models consistent across the domains?	For example, are the models that are used for performance the same models used for integrity/dependability analysis?
	Synthesis/Generation	Can the models be used for synthesis/generation of other related artifacts such as code, simulation, analysis, tests and documentation	
	Meta-Model/Model Transformations	Are the models used in one domain, or for one purpose, transformable into another domain where the well-defined semantics in one domain is carried through the transformation into the other domain; if so are they known to be consistent?	We know that one type of modeling is not always appropriate for everything, and that is why there is emergence of Domain-Specific Modeling languages; the key question is: are the models for one use consistent for other users (e.g., performance, integrity).
Virtual System Representation	Surrogate Integration	Are surrogates used to support analysis, and are the results of the surrogates captured so that they can be factored into modeling and simulation in the future?	Example, Formula 1 racing, uses data logging during physical experimentation and then factors results (and logs) back into simulation environment; can we fly some new capability on an existing aircraft and then factor the results from the test flights back into the modeling and simulation environments? This in the future should allow more virtual flight testing (once the approach becomes trusted).
	Formal Capability Assessment	How well do the models, simulations and analyses capabilities support the ability to understand the capabilities being developed?	Are the abstractions from the models still "rich enough" to be representative of the actual mission environment when used in a virtual environment? For example, if we use a 3D immersive environment, can we understand the physical characteristic of the operational system?
	Virtual Accuracy/Margin Analysis	Are the modeling, simulation and analysis accurate? How well do they allow the designers to understand the margins?	As an example, margin tolerances at the component level can propagate as the system is composed (or assembled). Are these factors understood and controlled?
	3D Immersive Environments	What is the degree to which 3D Immersive Environments are used to improve the understanding (and possibly training) of the virtual systems.	

Management Criticality Risks (Relates to Task 4)	Risk Management	Is there proper risk management identification, analysis and mitigations applied based on the use of models?	This should also consider: - Adequately deal with critical timelines - Integrated operational risk - Change management (model-based change management is different than document-based)
	Predictive Analytics	Are there models used to support a quantitative approach to risk management?	
Attributes of Modeling Maturity	Model-based metrics	Are there model-based metrics (or a comprehensive set of model measurements) and are they used to support the management of programs/projects?	The use of model-based metrics reflects on the modeling maturing of the organization.
	Multi-model interdependencies / consistency and semantic precision	If the organization is dealing with many different types of models, are the interdependencies managed and are the models semantically precise enough to manage model consistency?	Dealing with interdependencies and modeling consistency often deals with having a detailed understanding of the semantics across models. Positive results for this answer suggest a very advanced use of models.
	High Performance Computing (HPC)	Is HPC applied to the modeling, simulation and analysis efforts?	Use of HPC is an indicator of high modeling maturity.
Operational Risks (Relates to Task 4)	Procedures	Are the procedures for using the models understood, so that we can trust the model outputs to support other related types of analysis, both in terms of technical as well as risk?	This applies heavily in airworthiness (e.g., Mil Std. 516)
	Staff and Training	With the advances in the technologies associated with models, are the staff and training in place to support the use of models?	This is another indicator of a more advanced organization. As a side effect the use of 3D Immersive systems can be valuable in both collaboration and early training.
	Human Factors	How well are human factors supported by the modeling, simulation and analysis capabilities? This should consider Usability.	
Indirect support from Models	Certification	How well do the models-based automation and practices support certifications (if required)?	If not applicable use M - for Medium
	Regulation	How well do the models-based automation and practices support regulations (if required)?	If not applicable use M - for Medium
	Modeling and Simulation Qualification	How much do we trust our models?	

Acronyms and Abbreviation

This section provides a list of some of the terms used throughout the paper. The model lexicon should have all of these terms and many others.

AADL	Architecture Analysis & Design Language
ACAT	Acquisition Category
AGM	Acquisition Guidance Model
AP233	Application Protocol 233
ATL	ATLAS Transformation Language
ASR	Alternative System Review
BDD	SysML Block Definition Diagram
BNF	Backus Naur Form
BPML	Business Process Modeling Language
CAD	Computer-Aided Design
CASE	Computer-Aided Software Engineering
CDR	Critical Design Review
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
CORBA	Common Object Requesting Broker Architecture
CREATE	Computational Research and Engineering for Acquisition Tools and Environments
CWM	Common Warehouse Metamodel
dB	Decibel
DBMS	Database Management System
DAG	Defense Acquisition Guidebook
DARPA	Defense Advanced Research Project Agency
DAU	Defense Acquisition University
DoD	Department of Defense
DoDAF	Department of Defense Architectural Framework
DSL	Domain Specific Languages
DSM	Domain Specific Modeling
DSML	Domain Specific Modeling Language
ERS	Engineered Resilient Systems
HPCM	High Performance Computing Modernization
IBM	International Business Machines
IBD	SysML Internal Block Diagram
ICD	Interface Control Document
INCOSE	International Council on Systems Engineering
IPR	Integration Problem Report
IRL	Integration Readiness Level
ISO	International Organization for Standardization
IT	Information Technology
Linux	An operating system created by Linus Torvalds
MARTE	Modeling and Analysis of Real Time Embedded systems
MATRIXx	Product family for model-based control system design produced by National Instruments
MBT	Model Based Testing
MDA®	Model Driven Architecture®
MDD™	Model Driven Development

MDE	Model Driven Engineering
MDSD	Model Driven Software Development
MDSE	Model Driven Software Engineering
MIC	Model Integrated Computing
MMM	Modeling Maturity Model
MoDAF	United Kingdom Ministry of Defence Architectural Framework
MOE	Measure of Effectiveness
MOF	Meta Object Facility
MOP	Measure of Performance
MVS	Multiple Virtual Storage
NASA	National Aeronautics and Space Administration
NAVAIR	U.S. Navy Naval Air Systems Command
NAVSEA	U.S. Naval Sea Systems Command
OCL	Object Constraint Language
OMG	Object Management Group
OO	Object oriented
OSD	Office of the Secretary of Defense
PDM	Product Data Management
PDR	Preliminary Design Review
PIM	Platform Independent Model
PLM	Product Lifecycle Management
POR	Program of Record
PRR	Production Readiness Review
PSM	Platform Specific Model
RFP	Request for Proposal
ROI	Return On Investment
SE	System Engineering
SERC	Systems Engineering Research Center
SETR	System Engineering Technical Review
Simulink/Stateflow	Product family for model-based control system produced by The Mathworks
SCR	Software Cost Reduction
SDD	Software Design Document
SFR	System Functional Review
SOAP	A protocol for exchanging XML-based messages – originally stood for Simple Object Access Protocol
Software Factory	Term used by Microsoft
SRR	System Requirements Review
SRS	Software Requirement Specification
STOVL	Short takeoff and vertical landing
SVR	System Verification Review
SysML	System Modeling Language
TARDEC	US Army Tank Automotive Research
TRL	Technology Readiness Level
TRR	Test Readiness Review
UML	Unified Modeling Language
XMI	XML Metadata Interchange
XML	eXtensible Markup Language
US	United States
XSLT	eXtensible Stylesheet Language family (XSL) Transformation

xUML	Executable UML
Unix	An operating system with trademark held by the Open Group
VHDL	Verilog Hardware Description Language
VxWorks	Operating system designed for embedded systems and owned by WindRiver

Trademarks

Astah SysML is Copyright of Change Vision, Inc.

BridgePoint is a registered trademark of Mentor Graphics.

CORE is a registered trademark of Vitech Corporation.

IBM™ is a trademark of the IBM Corporation

iGrafx is a registered trademark of iGrafx, LCC.

Java™ and J2EE™ are trademark of SUN Microsystems

Java is trademarked by Sun Microsystems, Inc.

LDRA is a registered trademark of Trademark of LDRA Ltd. and Subsidiaries.

Linux is a registered trademark of Linux Mark Institute.

Mathworks, Simulink, and Stateflow are registered trademarks of The Mathworks, Inc.

MagicDraw is a trademark of No Magic, Inc.

MATRIXx is a registered trademark of National Instruments.

Object Management Group (OMG): OMG's Registered Trademarks include: MDA®, Model Driven Architecture®, UML®, CORBA®, CORBA Academy®, XMI®

OMG's Trademarks include, CWM™, Model Based Application Development™, MDD™, Model Based Development™, Model Based Management™, Model Based Programming™, Model Driven Application Development™, Model Driven Development™

ModelCenter, is a registered trademark of Phoenix Integration, Inc.

Model Driven Programming™, Model Driven Systems™, OMG Interface Definition Language (IDL)™, Unified Modeling Language™, <<UML>>™

OMG®, MDA®, UML®, MOF®, XMI®, SysML™, BPML™ are registered trademarks or trademarks of the Object Management Group.

PowerPoint is a registered trademark of Microsoft, Inc.

Real-time Studio Professional is a registered trademark of ARTiSAN Software Tools, Inc.

Rhapsody is a registered trademark of Telelogic/IBM.

Rose XDE is a registered trademark of IBM.

SCADE is copyrighted to Esterel Technologies.

Simulink is a registered trademark of The MathWorks.

Stateflow is a registered trademark of The MathWorks.

Statemate is a registered trademark of Telelogic/IBM.

UNIX is a registered trademark of The Open Group.

VAPS is registered at eGENUITY Technologies.

VectorCAST is a registered trademark of Vector Software, Inc.

Visio is a registered trademark of Microsoft, Inc.

VxWorks is a registered trademark of Wind River Systems, Inc.

Windows is a registered trademark of Microsoft Corporation in the United States and other countries.

XML™ is a trademark of W3C

All other trademarks belong to their respective organizations.

References

- [1] Allen, G. F. Hartman, F. Mullen, Dynamic Multi-level Modeling Framework, Results of the Feasibility Study, NDIA, October 2013.
- [2] Bergenthal, J., Final Report on the Identification of Modeling and Simulation Capabilities by Acquisition Life Cycle Phases, Johns Hopkins University/Applied Physics Laboratory, 16th Annual Systems Engineering Conference, October, 2013.
- [3] Bergenthal, J., J. Coolahan, Final Report on the Identification of Modeling and Simulation Capabilities by Acquisition Life Cycle Phases, NDIA Systems Engineering Division Meeting, February 2014.
- [4] Blackburn, M., A. Pyster, R. Dillon-Merrill, T. Zigh, R. Turner, Results from Applying a Modeling and Analysis Framework to an FAA NextGen System of Systems Program, NDIA, October, 2013.
- [5] Blackburn, M., A. Pyster, R. Dillon-Merrill, T. Zigh, R. Turner, Modeling and Analysis Framework for Risk-Informed Decision Making for FAA NextGen, INCOSE, June 2013.
- [6] Blackburn, M., A. Pyster, R. Dillon-Merrill, T. Zigh, R. Turner, Using Bayesian Networks for Modeling an Acquisition Decision-Making Process for the FAA NextGen Systems of Systems, NDIA, October, 2012.
- [7] Blackburn, M., R. Busser, H. Graves, Guidelines for Automated Analysis of System Models, Software Productivity Consortium Technical Report, December, 2000.
- [8] Blackburn, M., R. Cloutier, G. Witus, E. Hole, Transforming System Engineering through Model-Based Systems Engineering, System Engineering Research Center, RT-48, A008, Bi-monthly Status, December, 2013.
- [9] Blackburn, M., P. Denno, Virtual Design and Verification of Cyber-physical Systems: Industrial Process Plant Design, Conference on Systems Engineering Research, March, 2014; <http://dx.doi.org/10.1016/j.procs.2014.03.006>.
- [10] Blackburn, M., S. Kumar, Evolving Systems Engineering through Model Driven Functional Analysis, NDIA System Engineering Conference, October 2009.
- [11] Bleakley, G., A. Lapping, A. Whitfield, Determining the Right Solution Using SysML and Model Based Systems Engineering, (MBSE) for Trade Studies, INCOSE International Symposium, June, 2011.
- [12] Business Process Modeling Notation. Retrieved March 2010, from Wikipedia, The Free Encyclopedia: http://en.wikipedia.org/wiki/Business_Process_Modeling_Notation.
- [13] Browne, D., R. Kempf, A. Hansena, M. O'Neal, W. Yates, Enabling Systems Modeling Language Authoring in a Collaborative Web-based Decision Support Tool, Conference on System Engineering Research (CSER), March, 2013.
- [14] Coolahan, J. A Vision for modeling and simulation at APL, Johns hopkins APL Technical Digest, Volume 26, number 4 (2005).
- [15] Dahmann, J., BA. Aumber, M, Kelley, Importance of Systems Engineering in Early Acquisition, MITRE Corporation. Approved for Public Release; Distribution Unlimited Case # 09-0345.
- [16] DARPA, Producible Adaptive Model-based Software (PAMS) technology to the development of safety critical flight control software. PAMS has been developed under the Defense Advanced Research Projects Agency (DARPA) Disruptive Manufacturing Technologies program. Contract # N00178-07-C-2011, <http://www.isis.vanderbilt.edu/projects/PAMS>.
- [17] Darwiche, A., Modeling and Reasoning with Bayesian Networks, Cambridge University Press, 2009.
- [18] Defense Acquisition University, Defense Acquisition Guidebook Chapter 4 – Systems Engineering, May 2013; <https://acc.dau.mil/dag4>.
- [19] Department of Defense INSTRUCTION – INTERIM, NUMBER 5000.02 November 26, 2013.
- [20] Department of Defense MIL-HDBK-516B, Department Of Defense Handbook: Airworthiness Certification Criteria, Feb, 2008; http://www.everyspec.com/MIL-HDBK/MIL-HDBK-0500-0599/MIL-HDBK-516B_CHANGE-1_10217.
- [21] Firesmith, D., Are Your Requirements Complete?, Journal of Object Technology, Volume 4, no. 1 (January 2005), pp. 27-43, doi:10.5381/jot.2005.4.1.c3.
- [22] Henson Graves, H., S. Guest, J. Vermette, Y. Bijan, H. Banks, G. Whitehead, B. Ison, Air Vehicle Model-Based Design and Simulation Pilot, Lockheed Martin, 2009; available <http://www.omgwiki.org/MBSE>.
- [23] Hutchinson, J., J. Whittle, M. Rouncefield, S. Kristoffersen, Empirical Assessment of MDE in Industry,

- Proceedings of the 33rd International Conference on Software Engineering, 2011.
- [24] Khan, O., G. Dubos, J. Tirona, S. Standley, Model-Based Verification and Validation of the SMAP Uplink Processes, IEEE Aerospace Conference, 2013.
 - [25] Kim, H., Fried, D., Menegay, P., Connecting SysML Models with Engineering Analyses to Support Multidisciplinary System Development, American Institute of Aeronautics and Astronautics, 2012.
 - [26] Kim, H., Fried, D., Menegay, P., G. Soremekun, C. Oster, Application of Integrated Modeling and Analysis to Development of Complex Systems, Conference on Systems Engineering Research, 2013; <http://dx.doi.org/10.1016/j.procs.2013.01.011>.
 - [27] Leveson, N., A New Accident Model for Engineering Safer Systems, Safety Science, Vol. 42, No. 4, April 2004.
 - [28] Matei, I., C. Bock, SysML Extension for Dynamical System Simulation Tools, National Institute of Standards and Technology, NISTIR 7888, <http://dx.doi.org/10.6028/NIST.IR.7888>, October 2012, <http://nvlpubs.nist.gov/nistpubs/ir/2012/NIST.IR.7888.pdf>.
 - [29] Navy Integration and Interoperability (I&I) Integrated Capability Framework (ICF), Operational Concept Document, Version 2.0, 30 September 2013.
 - [30] OMG, MBSE Wiki, Ontology Action Team, <http://www.omgwiki.org/MBSE/doku.php?id=mbse:ontology>, 2014.
 - [31] Paredis, C., Y. Bernard, R. Burkhart, D. Koning, S. Friedenthal, P. Fritzson, N. Rouquette, W. Schamai, An Overview of the SysML-Modelica Transformation Specification, INCOSE International Symposium, Chicago, IL, July, 2010.
 - [32] Pearl, J. (1985). "Bayesian Networks: A Model of Self-Activated Memory for Evidential Reasoning" (UCLA Technical Report CSD-850017). Proceedings of the 7th Conference of the Cognitive Science Society, University of California, Irvine, CA. pp. 329–334. Retrieved 2009-05-01.
 - [33] Ray, S., G. Karsai, K. McNeil, Model-Based Adaptation of Flight-Critical Systems, Digital Avionics Systems Conference, 2009.
 - [34] Wagner, D.A., M. Bennett, R. Karban, N. Rouquette, S. Jenkins, M. Ingham, An Ontology for State Analysis: Formalizing the Mapping to SysML, IEEE Aerospace Conference, 2012.
 - [35] Wikipedia, Ontology, [http://en.wikipedia.org/wiki/Ontology_\(information_science\)](http://en.wikipedia.org/wiki/Ontology_(information_science)), 2014.
 - [36] Zentner, J., Ender, T., Ballestrini-Robinso, S., On Modeling and Simulation Methods for Capturing Emergent Behaviors for Systems-of-Systems, 12th Annual Systems Engineering Conference, October, 2009.
 - [37] Zimmerman, P., Model-Based Systems Engineering (MBSE) in Government: Leveraging the ‘M’ for DoD Acquisition, 2014 INCOSE MBSE Workshop January 25, 2014.
 - [38] zur Muehlen, M., D. Hamilton, R. Peak, Integration of M&S (Modeling and Simulation), Software Design and DoDAF, SERC-2012-TR-024, 2012.